PV PERFORMANCE MONITORING AND MODELLING IN SAUDI ENVIRONMENT

BY

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THESIS

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Dedicated to my parents, my wife, my siblings and my teachers

ACKNOWLEDGMENTS

I begin with the name of Allah, the most beneficent, the most merciful. May Allah bestow peace on our beloved Prophet Mohammed (*peace be upon him*), his family, his companions, and all those who followed him until the Day of Judgment.

All praise is due to Allah; we praise Him, seek His help, and ask for forgiveness. I then would like to show my deepest gratitude and respect to my parents, my beloved wife and my siblings. During this work my parents were a constant source of motivation and support. Their prayers love and encouragement helped me to arrive at this milestone.

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LIST OF ABBREVIATIONS

PV	:	Photovoltaic
LabVIEW	:	Laboratory Virtual Instrument Engineering Workbench
I-V	:	Current-Voltage
P-V	:	Power-Voltage
Rp	:	Parallel Resistance (Ω)
Rs	:	Series Resistance (Ω)
K_T	:	Temperature Coefficient
K_G	:	Irradiation Coefficient
DAQ	:	Data Acquisition
Voc	:	Open-Circuit Voltage (V)
Isc	:	Short-Circuit Current (A)
Irrad	:	Irradiation (W/m^2)
Temp	:	Temperature (K)
K_I	:	Current Coefficient
K_V	:	Voltage Coefficient

$\mathbf{V_m}$	:	Maximum Voltage (V)
$\mathbf{P_m}$	:	Maximum Power (W)
a	:	Ideality Factor
$\mathbf{I_D}$	:	Diode Current (A)
$\mathbf{I_L}$	:	Light Current (A)
STC	:	Standard Test Condition
$\mathbf{I_{mp}}$	:	Current at maximum power point (A)
$\mathbf{I_o}$	:	Diode Saturation Current (A)
$\mathbf{I_{PV}}$	:	Photovoltaic Current (A)
$\mathbf{I_{SH}}$	:	Current in Shunt branch (A)
k	:	Boltzmann's Constant (J/K)
Ns	:	Number of series connected cells in PV panel
$\mathbf{P_{mp}}$	:	Power at maximum power point (W)
q	:	Electronic Charge (Coulombs)
$\mathbf{V_{mp}}$	:	Voltage at maximum power point (V)
ASTM	:	American Society for Testing and Materials
CdTe	:	Cadmium Telluride

AC	:	Alternating Current (A)
DC	:	Direct Current (A)
I_m	:	Maximum Current (A)
MPPT	:	Maximum Power Point Tracker
Vmpp	:	Maximum Power Point Voltage (V)
Impp	:	Maximum Power Point Current (A)
η	:	(Eta) Efficiency
P_L	:	Power at Load (W)
FF	:	Fill Factor
MATLAB	:	Matrix Laboratory
Rsh	:	Shunt Resistance (Ω)
PC	:	Personal Computer
SAS	:	Solar Array Simulator
IBM	:	International Business Machines
ISDN	:	Integrated Services Digital Network
FP	:	Field point
IEC	:	International Electrotechnical Commission

IEAPVPS	:	International Energy Agency Photovoltaic Power System
MGTC	:	Malaysian Green Technology Corporation
MMD	:	Malaysian Meteorological Department
DG	:	Distributed Generator
EV	:	Electric Vehicle
HEV	:	Hybrid Electric Vehicle
FMECA	:	Failure Mode Effects and Critical Analysis
NI	:	National Instrument
VI	:	Virtual Instrumentation
T	:	Temperature (K)
P	:	Power (W)
V	:	Voltage (V)
I	:	Current (A)
$\mathbf{V_t}$	:	Terminal Voltage (V)
$\mathbf{V_{tn}}$	:	Terminal Voltage at STC (V)
$\mathbf{T_n}$	:	Temperature at STC (K)
$\mathbf{I_{pvn}}$	:	Photovoltaic Current at STC (A)

G	:	Solar radiation intensity (W/m^2)
G_n	:	Solar radiation intensity at STC (W/m^2)
I_{on}	:	Saturation Current at STC (A)
P_{max}	:	Maximum Power (W)
$P_{max,e}$	:	Experimental Maximum Power (W)
$P_{max,m}$	:	Calculated Maximum Power (W)
I_{scn}	:	Short Circuit Current at STC (W)
MPP	:	Maximum Power Point
Eg	:	Semiconductor band gap (eV)
R_{pmin}	:	Minimum Parallel Resistance (Ω)
KFUPM	:	King Fahd University of Petroleum and Minerals
CPU	:	Central Processing Unit
USB	:	Universal Serial Bus
I/O	:	Input-Output
MAX	:	Measurement and Automation Explorer
COM	:	Communication port
VISA	:	Virtual Instrument Software Architecture

$\mathbf{K_{TV}}$	:	Voltage Temperature Coefficient (V/K)
$\mathbf{K_{GV}}$	:	Voltage Irradiation Coefficient ($V/W/m^2$)
$\mathbf{K_{TI}}$	;	Current Temperature Coefficient (A/K)
$\mathbf{K_{GI}}$	:	Current Irradiation Coefficient ($A/W/m^2$)
C	:	Linearity Factor Constant
μ	:	Mean (mu)
σ	:	Standard Deviation (Sigma)
∞	:	Infinity
π	:	Pi Costant
$\mathbf{V_{ocn}}$	:	Open Circuit Voltage at STC
Normcdf	:	Normal Cummulative Distribution Function
$\mathbf{I_{effect}}$	:	Effective Current (A)
$\mathbf{V_{effect}}$	:	Effective Voltage (V)

ABSTRACT

Full Name : [Syed Essamuddin Ahmed]

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This thesis presents and discusses the modelling, analysis, monitoring and performance evaluation of PV system. The two installed PV generator system is operating in extreme and severe weather conditions. The local area is characterized by high level of irradiation, high humidity variations, very high ambient temperature and frequent dust storms. Each PV panel is of 150 W rating feeds a variable resistive load separately and simultaneously.

A generalized Photovoltaic (PV) array model is developed in LabVIEW (Laboratory Virtual Instrument Engineering Workbench) based on equivalent electric circuit model. Various approaches to PV system modelling are investigated and various studies are conducted using the developed models. These included studies to evaluate the electrical performance of the module under different environmental and operating conditions.

In LabVIEW, the measurement is taken through a conditioning amplifier and NI data acquisition equipment. The constructed LabVIEW engine displays environmental parameters and the associated electrical variables (voltage, current and power) on dedicated graph windows continuously in a real time manner with the desired frequency of measurement and storage rate. The I-V and PV characteristics are taken for any chosen

panel, displayed and stored accurately. LabVIEW allows appending any characteristics for the sake of comparison, investigation and research purposes.

The monitoring results are very satisfactory. The online data display in multi-scale window frame is very informative. The online efficiency evaluation is very useful for the system operation and analysis. Rs and Rp model as well as the improved model results are shown satisfactory with dust index. The obtained results is validated against simulation to show very good degree of accuracy. The measurement system has shown clearly the impact of dust, the impact of high temperature and the impact of the irradiation changes on the PV panel efficiency. The developed system is found very supportive for research and educational purposes.

ملخص الرسالة

الاسم الكامل :**[** سيد عصام الدين احمد**]**

عنوان الرسالة : [مراقبة أداء الخلية الشمسية وتصميمها في البيئة السعودية**]**

التخصص : [الهندسة الكهربائية**]**

تاريخ الدرجة العلمية: **[**أبريل- 2014**]**

هذه الرسالة تعرض وتناقش تصميم ، تحليل ، مراقبة وتقييم الأداء لنظام الخلايا الشمسية. تم تركيب نظامين من أنظمة التوليد الشمسية تحت ظروف بيئية قاسية جدا. حيث أن المنطقة المحلية توصف بأنها ذات اشعاع عالي، ورطوبة عالية ومتغيرة بالاضافة لكونها ذات حرارة عالية وذو عواصف رملية متكررة. كل واحدة من لوحات التوليد الشمسية تزود بما يصل الى 150 واط كحد أقصى وتزود حملا مقاوما متغيرا بشكل منفصل وفي آن واحد.

نظام الخلايا الشمسية اللوحية تم تمثيلها باستخدام برامج LabVIEW (والذي يعني اختصارا بطاولة العمل لمختبر الأجهزة الهندسية الافتراضية) بناء على تصميم الدائرة الكهربائية المكافئة للخلية الشمسية. تم فحص ودراسة نماذج متعددة من الخلايا الشمسية باستخدام التصاميم المتطورة. حيث أن هذه الدراسات تهدف الى تقييم الأداء الكهربائي للخلايا الشمسية تحت ظروف بيئية وتشغيلية ومختلفة.

في برنامج LabVIEW تم أخذ القياسات من خلال المضخمات ومن خلال أجهزة جمع البيانات الخاصة بشركة NI . محرك LabVIEW الذي تم بناؤه يعرض المتغيرات البيئية والمتغيرات الكهربائية المرتبطة (كالفولتية والتيار والقدرة) على شاشات عرض مكرسة لذلك وبشكل مستمر في الزمن الحقيقي بمعدلات قياس وتخزين مناسبة.

خصائص الخلايا الشمسية والعلاقة ما بين الجهد والتيار V-I يتم أخذها لأي لوحة شمسية حيث يتم عرضها وتخزن بشكل صحيح. يسمح برنامج LabVIEW بإرفاق أي خصائص في سبيل المقارنة و الفحص و في سبيل الأهداف البحثية.

النتائج التي تمت مراقبتها وقياسها وتخزينها مرضية، البيانات المعروضة في الزمن الحقيقي على الشاشات المختلفة للبرنامج مليئة بالمعلومات حيث أن تقييم الفعالية بالزمن الحقيقي مفيد جدا لأنظمة التشغيل والتحليل. التصميم الذي يعتمد على المقاومة التسلسلية Rs و المقاومة التفرعية Rp بالاضافة الى نتائج التصاميم المحسنة أظهرت أنها نتائج مرضية مع مؤشر الغبار.

النتائج التي تم الحصول عليها تظهر مصداقيتها بالمقارنة مع نتائج التحليل المعتمدة على المحاكاة حيث تظهر درجة جيدة من الدقة. نظام القياس يظهر بوضوح تأثير الغبار بالاضافة الى تأثير الحرارة العالية و التغير الاشعاعي على فعالية اللوحات الشمسية. النظام المطور يظهر مدى دعمه للجانب البحثي والتعليمي على حد سواء.

CHAPTER 1

INTRODUCTION

Photovoltaic cell is a fundamental device for PV Systems. Such systems consist of multiple components based on electrical connections and mechanical components like mountings and different way of regulating and modifying the electrical output.

1.1 Solar Resource:

Solar energy has progressed more than any other renewable resource. The energy is obtained from the radiations that are electromagnetic waves emitted by the sun. As the distance between sun and earth is much larger, very small part of solar radiation reaches earth surface which becomes more lessened due to ions and dust particles. Sunlight received on any earth surface depends on several factors such as timings of the day, landscape, weather, season and geographical locations. The solar radiation intensity, which reaches earth surface directly, is approximately 1370 W/m^2. This intensity value is named as solar constant. So, earth surface receives solar energy equal to 3.2 EJ/y. By comparing this energy to global energy consumptions, it becomes 7000 times more than the required energy. If this available energy or even of a part of it can be harvested, the global energy problems, then, could be solved.

Photovoltaic efficiency depends on spectral distribution of sun but these are of two types, defined by photovoltaic industry and the (ASTM) American Society for Testing and Materials. The normal standard in which the solar radiation has dependence on the distance travelled (air mass). Other one is the global standard in which diffused radiations spectrum is considered. The solar radiation becomes diffused due to atmospheric conditions like dust and clouds. Pyranometer is used to measure these diffused radiations. This instrument measures solar radiation for each wavelength, hence, it gives total power value accurately.

1.2 Normal Test Conditions:

Performance of different PV units can be compared based on uniform or standard conditions. The parameters of PV units or cells are, generally, given in a manufacturer's datasheet. Following standard test conditions (STC) are used for Measurements:

Irradiance = 1000 w/m^2

Ambient temperature = 25 C

Spectral distribution with air mass = 1.5

1.3 Introduction to Photovoltaic:

The most important part of photovoltaic systems is the photovoltaic cell. The working of photovoltaic, their electrical performance and modelling issues are discussed in following sections.

A PV cell is a semiconductor diode as shown in Figure 1, working on the principle theory of photoelectric effect which defined as any material exposed to light generates charge carriers. Solar radiations are basically photons of different frequencies and energies. Each material has band gap between conduction and valence bands and electrons goes into conduction bands when the energy of incident photon becomes greater than band gap energy. Now, electric field is applied to drift conduction band electrons in semiconductor material and this movement of electrons is called current. A metal plate is usually deposited on bottom and top of PV cells to collect the current for external use. Hence, bad gap energy corresponds to threshold energy which in turn gives threshold frequency of a semiconductor material. In photovoltaic material, photoelectric emission rate can be increased by increasing light intensity.

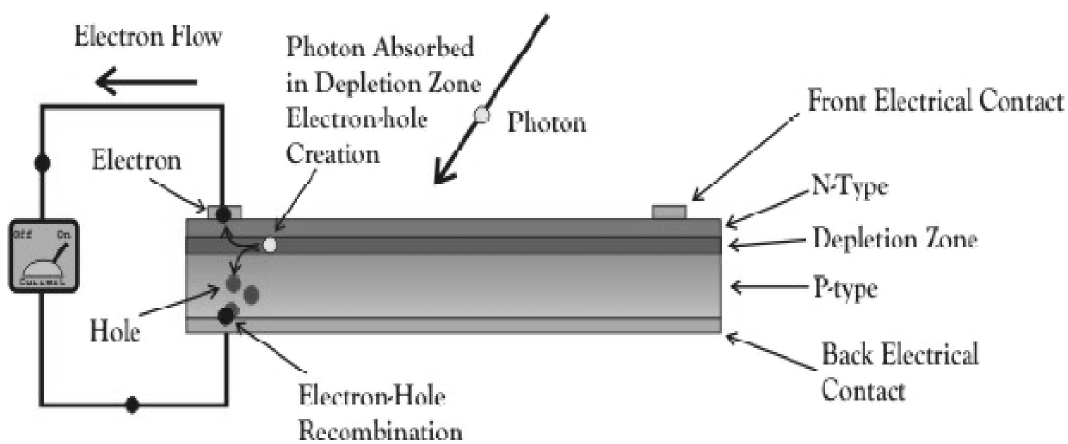


Figure 1: Photo electric effect of PV cell

1.4 Materials Used In PV Cell:

Photovoltaic cells are made of semiconducting materials that produce electric current from solar radiation. There are types of solar cells available commercially: one is thin film solar cells and second is crystalline silicon solar cells.

1- Crystalline materials

Crystalline silicon cells can be sub-categorized as:

Mono-crystalline Silicon

In this type, each cell has a single crystal and it is much efficient than other crystalline cells due to good electrical, physical and chemical characteristics of silicon. These cells are very expensive.

Polycrystalline Silicon

The polycrystalline silicon cells are better than mono-crystalline silicon cells in respect of simpler and cost efficient manufacturing process. In this type, each cell has more than one crystal. These cells are less efficient that mono-crystalline silicon cells.

2- Thin film materials

In these cells, semiconductor films are very thin which are deposited on low cost substrate like glass, metal or plastic. Hence, it is less expensive but its efficiency is also lower than other types of PV cells. The light absorbing material requirement s are reduced from these cells. Many types of thin film materials are available.

Amorphous silicon

Such type of materials is highly defective even with hydrogenation, resulting in low lifetime of minority carrier and less conversion efficiency. These materials can be manufactured on low temperatures and less energy. Hence, they are cost effective in manufacturing. The performance of such materials degrades when they are exposed to sun, which is their major drawback.

Cadmium Telluride (CdTe)

The materials cadmium and tellurium are used to form a poly-crystalline compound. During manufacturing of PV cells, cadmium telluride is usually sandwiched with cadmium sulphide. Among all thin film technologies, this CdTe poly-crystalline compound has the lowest production cost. In this technology, the substrate used is soda-lime glass (low cost).

Copper Indium Selenide

Such type of compound semiconductor material is composed of indium, selenium and copper. The material copper indium selenide is a firm solution and unlike amorphous silicon, this compound made solar cell that does not degrade under light intensity. However, it is much costly due to its complex manufacturing process.

Gallium Arsenide

Gallium and arsenic materials are used form this semiconductor compound. GaAs is much efficient than silicon but it is also much expensive. It is used in many applications like space, concentrator systems etc.

1.5 PV Cells, Modules and Arrays:

Typically, a photovoltaic cell gives voltage of 0.5 to 0.8 V at the output. This voltage output of a PV cell depends on the semiconductor material. Each PV cell power production is very low, so numbers of photovoltaic cells are used in series to make a photovoltaic module as shown in Figure 2. Photovoltaic modules, commercially available, have 36 or more PV cells joined in series. Photovoltaic modules are joined in parallel and series fashion to make PV arrays. So, PV cells are either connected in series to add voltages of each cell with same current (for high voltage requirement) or connected in parallel to add current passing through each PV cell with same voltage (for high current requirement) to get desired power.

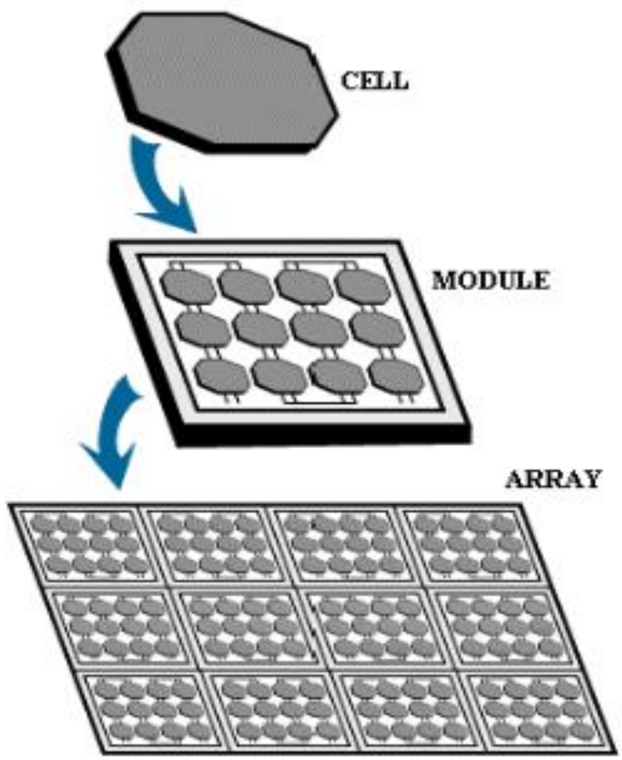


Figure 2: PV cells, modules and arrays

1.6 Photovoltaic Systems:

Different interconnected components are used to make Photovoltaic systems. The applications of photovoltaic system range from providing power to small devices to feed electricity to main grid. There are mainly two types of photovoltaic systems, stand-alone system and grid connected system as shown in below Figure 3. The major difference between the two PV systems is the load demand that should be matched with solar energy output which known as stand-alone system. When PV systems are used with other power sources like wind or thermal generators, then, it is classified as hybrid system.

1- Standalone systems

Stand-alone systems were the first cost-effective photovoltaics application especially in remote areas where connection to utility grid was not feasible. This system will extended for rural electrification in the developing world. This system is also used for water pumping system, communication system and mobile equipments. In general, this system comprises of control and power conditioning units (inverters, converters), storage elements with solar modules and the load.

2- Hybrid systems

In cases where the requisite energy from photovoltaic modules is not practically feasible and economical other means such as diesel generator used in conjunction with PV systems. Thus this system ensures the demands of energy are met while photovoltaic supply is utilizing fully.

3- Grid connected systems

Grid connected photovoltaic systems energized by PV connected to main utility grid that actually provides opportunity while protecting the environment to adequate energy. Governments are putting legislations for installation witnesses to encourage the use of such systems.

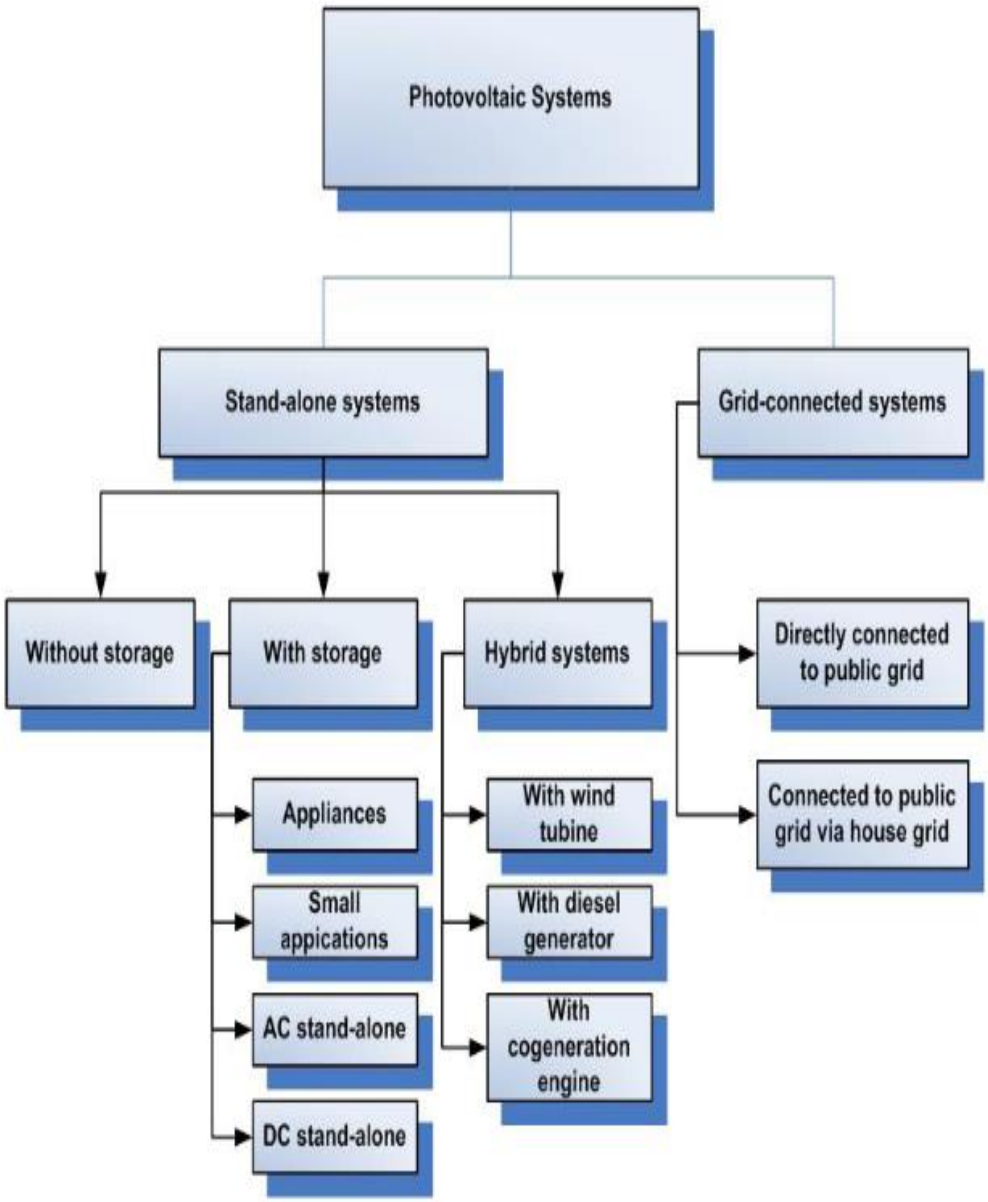


Figure 3: Classification of photovoltaic system

1.7 Photovoltaic Performance:

The electrical performance of a PV cell, module or array is determined by the solar radiation absorbed in the cell, the cell temperature and external load attached to the cell. The performance is analyzed and evaluated through the characteristics of a cell.

1.8 Characteristics Of A PV Cell

The main three significant parameters on the photovoltaic characteristics are open circuit voltage (Voc), short circuit current (Isc) and maximum power point (Vmp, Imp). The maximum power that achieved from photovoltaic cell is occurs at a point on the bend in the I-V curve known as the maximum power points. The typical I-V relationship of a photovoltaic cell is shown in Figure 4. Generally, these parameters are provided in the datasheet by manufacturers of a particular photovoltaic cell or module. When the PV cell is connected to an external load, the electrical characteristics of the load determine the actual point on the I-V curve at which the photovoltaic cell operates. PV cells are often connected to the load through a MPPT (maximum power point tracker) which regulates cell voltage so that cell operates at maximum power point. I-V curve shape is same and does not change for module or array of photovoltaic cells but it is scaled which depends on number of cells joined together. Environmental parameters such as ambient and cell temperatures, irradiance, wind speed and dust affects the shape by disturbing the maximum power points on I-V curve.

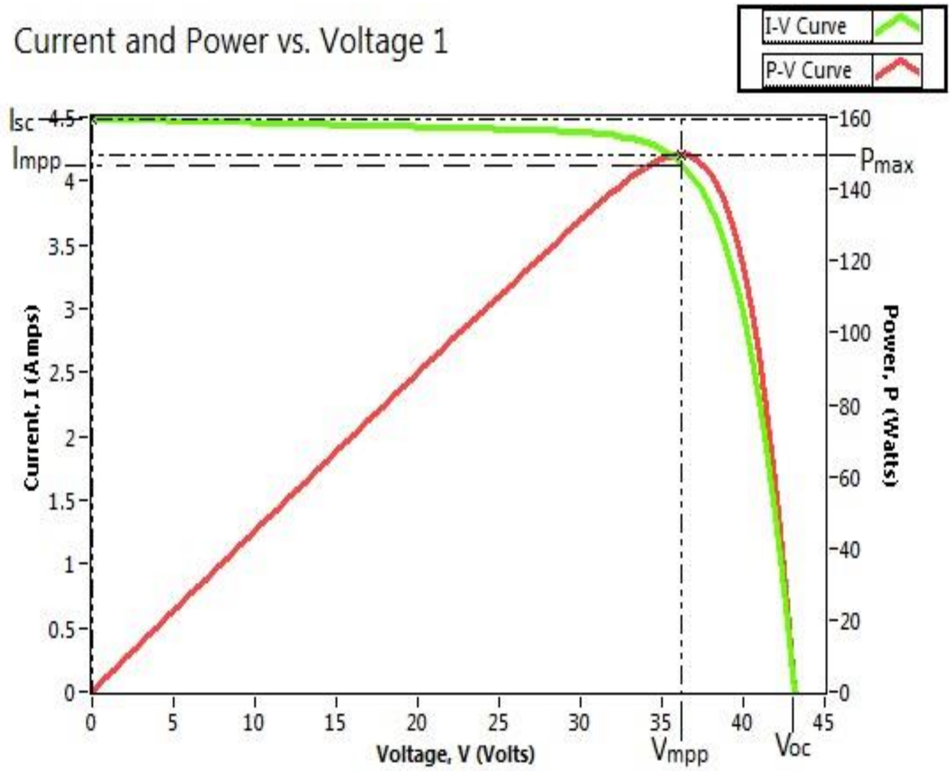


Figure 4: I-V characteristic of PV cell

One more essential parameter of the photovoltaic characteristics is known as the Fill Factor (FF). The fill factor is basically determines the quality of the solar cell. PV cell operation is better when the fill factor value is close to unity.

$$FF = \frac{V_{mpp} * I_{mpp}}{V_{oc} * I_{sc}} \tag{1}$$

Efficiency (η): The ratio of maximum electrical power (Pmp) output to solar power (PL) input that received by the cell surface is defined as efficiency:

$$\eta = \frac{V_{mpp} * I_{mpp}}{PL} \tag{2}$$

The PV industry’s future is promising as the quality of PV modules continues to increase. Higher efficiencies cell and modules are expected in future due to the continuous improvement of manufacturing processes and technologies. For the next decade, crystalline silicon devices are expected to remain dominant due to the material availability and cost.

CHAPTER 2

LITERATURE REVIEW

2.1 Modelling

Photovoltaic system modelling is crucial for designers which should be competent to generate electrical output characteristics such as P-V & I-V relationship of photovoltaic panel under different atmospheric conditions. Over the years, several models are developed to analyze the performance of photovoltaic system including cell analytical information, experimental correlation and with the combination of two methods.

In the beginning the simple method of scaling radiation and temperature of maximum power point [1] introduce by Menicucci to measure the PV performance at one point. Authors, Hishikawa and Marion in [2], [3] proposes I-V curve translation method from one to another atmospheric condition and radiation level. Marion [3] extends and develops bilinear interpolation model which uses experimentally determined four I-V curves that are interpolated with open-circuit voltage and short-circuit current for temperature and radiation. These models require large data and are relatively complex.

The practical and competent PV model simulation is proposed by King in [4] named as Sandia Lab PV model in which currents and voltages are calculated at five points by taking temperature, irradiation and wind speed as inputs. This model requires thirty determined coefficients to analyze the PV performance whose values are available for several commercial photovoltaic modules [5]. Thus power system studies are not easy due to complication and also it requires high computational time.

Another approach is representing the model with an equivalent electric circuit which is much appropriate for power electronics converter due to its electrical circuit nature. This type of model can be classified as three, four, five and seven parameter models for ideal diode, Rs model, Rsh model and double diode model respectively.

The three parameter or ideal diode model is the most simplest which consist of radiation dependant current source and diode [6], [7], [8]. Saturation current, photo-current and diode constant are the main three parameters requires for generating PV characteristics. This model is extended by adding series resistance to characterize I-V curve known as Rs model or four parameter model [9], [10], [11], [12], [13], [14]. Townsend [9] proposes Rs model for PV direct coupled systems. Chenni [14] develops an approach to execute the Rs model in MATLAB programming environment to analyze PV performance with data provided in datasheet. This easy model requires cell temperature and irradiation as input to evaluate the performance that is not feasible for low irradiation and high temperature presented by Ishaque in [15] and also fails to guess the thin film technologies performances such as amorphous silicon based PV panels, De Soto [16].

An extended and improved photovoltaic model is developed by adding shunt or parallel resistance that considered to be finite value known as five parameter or Rsh model [16], [17], [18], [19]. De Soto [16] proposes and shows a comparison of five parameter model results with Sandia Labs model, Celik in [12], for crystalline photovoltaic panels and finds better performances under different environmental conditions. Author, Villalva in

[19] presents a new methodology in which the parameters for the model are determined by adjusting the curve at three points giving least error at these points: open circuit, maximum power, and short circuit. In [20] by Brano develops a new variation of the 5 parameters model accounting more precisely for environmental changes based on a trial and error process. Campbell [21] develops a piecewise linear model for transient and dynamic analysis of photovoltaic system which is an advantage over other nonlinear photovoltaic models. An attempt is made to improve the model by inclusion of plane-of-array radiation correction factor by Boyd [22] but concludes inconsistent improvement in accuracy.

Several other researchers studies photovoltaic performances under partial shaded condition [23], [24], [25], [26]. Effect of partial shading on PV output curve is describe in [24] by Kawamura, presented experimentally in [25] by Patel and MATLAB based modeling is carried out in [26] by Patel that shows multiple peaks on P-V characteristics. Patel and Agarwal [25] propose method in MATLAB for PV performance of inhomogeneous shading conditions. ANN methodology is introduced in [27] by Karatepe for PV performance of partially shaded photovoltaic arrays.

Some researchers use seven parameter or two diode model to further extend the circuit based model [15], [28], [29], [30]. The comparison with Rsh and Rs model is presented in [15] by Ishaque, shows inefficient performance of two diode model due to the assumption of some parameter values. The five parameter model is extensively used in literature due to the simplicity and accuracy as describe by Carrero in [17].

The necessary and complicated task is the unknown parameter values estimation in the implementation of photovoltaic electric circuit model which is not included in manufacturer's datasheet. Several methods have been used in literature for the estimation of these parameters [30], [31], [32], [33], [34], [35]. Some researcher uses analytical equations and iterative algorithms while assuming one parameter value and determine other parameter values [10], [14], [19], [36], [37], [38]. In [37] by Walker, Rsh is considered infinity and thus ignored and diode constant is taken constant and calculate other parameters by solving the analytical equations. In other papers [10], [14] by Yeong-Chan Kuo and Chenni, Rs and diode constant are computed by an iterative method while ignoring the effect of Rsh. Townsend [9] and Villalva [19] assume one of the parameters explicitly and solves for the remaining parameters using iterative processes. The author, Carrero in [39] determines all five parameters value by an iterative algorithm. These methods use the data provided in datasheet to analyze PV performance based on three key points of I-V curve such as maximum power, open circuit and short circuit points and validated their model under different operating conditions.

Due to extremely nonlinear nature of I-V equations, direct solution by solving simultaneously is not an easy task. Authors, De Soto and Boyd in [16] and [22] use nonlinear equation solver software to overcome this problem and found out the model parameters by solving five equations.

Several authors use another technique named intelligent and optimization method for model parameters estimation such as genetic algorithms [31] by Zagrouba, multivariable Levenberg-Marquardt optimization method [32] by Charles, fuzzy Logic [40] by Elhagry and artificial neural network [41], [42] by Almonacid and Syafaruddin to determine the parameters value.

2.2 General Overview

The growing usage of renewable energies to sustain development that resulted in installation of considerable amount of renewal power plants, e.g. wind, photovoltaic, wave powers etc. development during last few decades all over the world. Renewable energies are greatly needed as alternatives to stay away from economic breakdown as fossil fuels, or conventional resources, are depleted rapidly due to the increasing demand of power and consequently inferior standards of living around the world. Photovoltaic system has gained a lot of potential in the recent years due to the depletion of traditional energy resources. A free and virtually unlimited source of energy can be tapped from the nature saving expensive and limited energies such as oil and natural gas. One of energy sources is the solar energy, which is readily available and can be tapped easily as discussed by Ramanathan [43]. Different ways have been used to analyze the output characteristics of solar panels and silicon solar cells by researchers, using different software such as MATLAB, LabVIEW etc.

The performance evaluating and monitoring of PV systems based on microcontroller DAQ system is introduced by Chang [44]. Under real operating condition and based on simulation of single diode PV model, the estimated data is compared with measured data. The literature also reveals the similar work using microcontroller for PV systems [45], [46], [47], [48] and PV applications [49], [50]. Performance monitoring and measurement system for integrated PV based solar insulation has been studied by Husain in [51]. They use microcontroller as hardware and visual basic as software for the monitoring system.

Flexible and controllable operation of system is carried out directly through computer instead using microcontrollers, Easwarakhanthan [52]. Three parameters voltage, current and temperature for standalone PV system are vital and DAQ can measure many varieties of readings, Buller [53]. The prototype of standalone PV monitoring system using solar array simulator, data acquisition, a battery array and personal computer has been developed by Ramanathan [43]. Firstly solar power is generated by SAS that transfers to the battery array and battery data is monitored through DAQ at specified interval. All calculations, measurements and analysis are carried out in PC. Somchai Hiranvarodom [54] has investigated different standalone PV panels that are installed in Rajamangala University of Technology Thanyaburi, Thailand and presents the development progress for PV systems. He considers the operational information such as reliability, acceptability, maintenance and user satisfaction with system performance monitoring over two years period.

Electrical performance estimation has been studied using designed measurement system of PV module by Kwak in [55]. The data measurements are obtained from measurement studio and visual studio Basic.Net (2005), National Instrument, equipped with interface and operated by a general IBM-PC.

The literature reveals some VI concept for the performance of PV power plant, Aristizabal [56]. The real time performance of PV plant and energy generated is monitoring using equipment. Recently, LabVIEW based monitoring systems have been developed for PV-power generation systems [57], [58], [59], [60]. Based on VI that uses novel procedure, the monitoring of PV solar plants is developed by Forero [59].

Data acquisition has been used to develop new design method for various residential PV systems. Measurement data automatically stored in site PC after 1-min interval and once in a day transferred to host computer through ISDN telephones line in Hamamatsu, Sugiura [61].

X. Zou, L. Bian, Z. Yonghui, and L. Haitao [62], presents and discusses Field Point (FP) I/O modular high precision devices as hardware for processing and measuring data and DAQ card as software. LabVIEW used to process and display electrical output parameters and environmental variables and store in PC hard disk.

Vergura and Natangelo [63] propose the PV assessment by data analysis in the integrated LabVIEW and Matlab environment. They compare the data of a specific date with the ones of the same date of a previous year. Therefore, some literature [12], [16], [17], [19], [64] contribute to the parameter extraction for a single diode PV model based on the experimental data of manufacture's datasheets under standard test condition (STC). The practical model consists of diode, photo current, series internal resistance and parallel resistance for leakage current, Kim [65], [66].

PV system has been rising worldwide to produce electricity and more renewable sources are penetrating per governmental policies. Furthermore, new regulatory laws mandating the use of renewable energy have expanded this market around the world. For continuing development of the PV industry and to evaluate and analyze the quality and performance of PV connected with grid system is demonstrated in [47], [49], [67], [68]. A similar work for monitoring and evaluating performance in real time and the system testing to measure electrical and environmental variables of grid connected PV system has been published. The standard IEC 61724 [69] and framework of the (IEA PVPS) International Energy Agency Photovoltaic Power System program task is followed for variable selection, Jahn [70].

In the standard the integration of PV systems to electricity networks is covered in two main categories: safety and power quality. Few studies also describe for large scale PV power plants. One of these studies is an overview and measurement on quality assurance, Kiefer [71]. Areas discusses include module testing, onsite system testing, power rating, yield monitoring and yield assessment. Analysis and performance results of large scale PV system of 80 kW have been presented by Jung in [72]. They analyze and evaluate the performance of PV system and showing the outcome on the operation characteristics of environment conditions. Author, Pietruszko in [73] investigates the installed grid connected 1-kW PV system in Poland and discusses the performance over eight year's operation. In, Rahman [74] the performance based on monitoring data of a grid connected PV system, 45.36 kWp, installed at MGTC (Malaysia Green Technology Corporation) are elaborated. David L. King [75] develops a method that helps to specify and portray the PV system value and performance to financial institutions and customers. Product quality and evaluating products are vital tools for end customers and systems integrators to guide future decision-making, Marion [76].

In [77] the author, Hussin mainly focuses on the significance and the effect of solar irradiance pattern for PV system design in Malaysia. This also presents the daily global solar radiation with average of solar radiation over 10 years of monitoring data by MMD

(Malaysian Meteorological Department). One of the latest studies by Lopez also publishes [78] the implementation of wireless remote control and monitoring system of a solar PV-DG (photovoltaic distributed generator) for micro-grids applications. Some studies have developed concept in the use of a monitoring system to enhance the degree of efficiency of PV. One of such studies of electric vehicles (EVs) as well as hybrid electric vehicles (HEVs) is focused as potential target applications, Schuss [79].

Several other recent studies have focussed on the efficiency evaluation of photovoltaic panels having consideration of dust and pollution on the surface of the panels. An experimental activity of PV modules based on electrical characterization is focused by Catelani in [80]. A numerous PV modules are exposed to different metrological conditions and analysis has been done for efficiency degradations.

Usually, design, radiation analysis, sizing and efficient operating strategies have explored in research and development of such systems. In literature, e.g. [81], [82], [83] the PV modules are analyzed in terms of I-V characteristics or panel modeling. The exposure of dust on PV modules and analysis concerning the performance is introduced by Catelani in [84] by means of a (FMECA) Failure Modes, Effects and Criticality Analysis, Lazzaroni [85]. The phenomena that lead to photovoltaic system failure and degradation are identified by such techniques and to determine devise methods and their consequences for minimizing their occurrence, Meyer and Mishra [86], [87]. Snow and ice also affects the output power of photovoltaic cells but efficiency reduction is incredible for thick ice layer, Powers [88]. Authors in [89], [90], [91], [92] explores thoroughly the efficiency degradation of PV panels due to the influence of dust. The factors that influenced in dust settlement on PV panels are shown briefly in Figure 5[91][61].

A regular cleaning is suggested in order to exploit the efficiency [93]. A test chamber and sun simulator are designed and described by Catelani in [84]. The maximum power is measured before and after cleaning the photovoltaic panel and impact of dust is quantified.

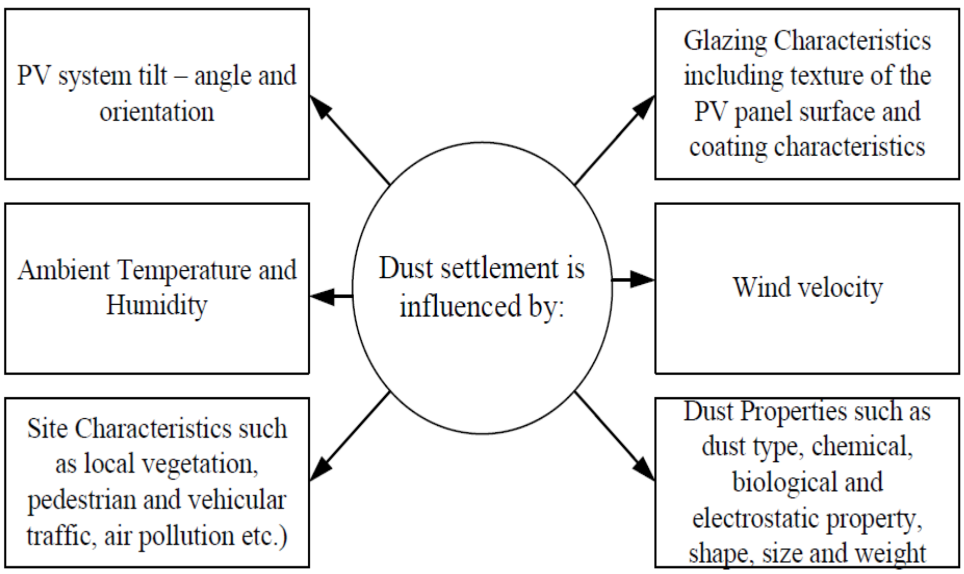


Figure 5: Dust settlement factors on PV panel

In this thesis, monitoring the PV performance and experimental system testing for measuring electrical parameters and metrological parameters for standalone PV system is proposed. Automatic data acquisition, DAQ, technology made by NI, National Instrument is used as hardware for monitoring PV-system performance. The DAQ system based on LabVIEW package software is used to display, store, and process the collected data in the computer hard disk.

CHAPTER 3

THESIS OVERVIEW

No other natural resource is as plentiful as sunlight. Available just about everywhere on earth, the sun is increasingly being used to provide free, clean source of renewable energy. Scientist and engineers helps in harness this abundant resource and address escalating environmental and energy concerns. National instruments have played an important role throughout this process from being used to research and develop new technologies, to testing each solar panel produce.

3.1 Outline of the Thesis:

The thesis is structured as follows.

Chapter 1 presents brief description and background knowledge about solar resource, photovoltaic cells, materials and modules to understand future parts of the thesis. PV theory is presented and solar related terms and performance measures of PV are defined. The different types of PV systems are outlined and described.

Chapter 2 provides brief details on previous work and literature survey on PV technology.

Chapter 3 presents brief overview, objective and methodology of the thesis.

Chapter 4 describes the modelling technique simulation and parameter extraction techniques of the PV panels.

Chapter 5 describes the set-up and development of program for monitoring and analyzing parameters in software environment.

Chapter 6 presents various range of analysis of data acquisitions that are used and constitute PV system.

Chapter 7 investigates the performance, and results and discussions are presented.

Chapter 8 concludes the thesis work and gives directions for future work.

3.2 Motivation, Programs and Problem Description:

Solar energy is the major renewable energy source in the world and existing in all over the place in different quantities. Presently, PV generation systems are being promoted to mitigate environmental issues like air pollution and the green house effect. PV panels do not have moving parts, generate no emissions and operate silently. Also, solar technology is greatly modular and can be scaled easily to supply the required power for loads.

PV panels are usually used in three main fields: Satellite applications, Off-grid applications, where solar arrays are used to power remote loads that are not connected to the electric grid, and On-grid or grid connected applications. PV panel output power and efficiency would effects due to the uncertainty of the irradiation, temperature and dust that causes security and stability issues to power system. The efficient and superior parameter monitoring system can easily be used to monitor and analyze PV system. Also, an accurate PV model is required that can simulate its output characteristics with the change in environment conditions, i.e irradiation, ambient temperature, cell temperature, and dust to study and analyze the impact of PV generation on power system.

Modeling is a very essential part of engineering practice. Availability of models of the PV generator in system development at all stages is very significant in monitoring, system sizing and cost analysis. Thus with the use of powerful software and computers, the performance of complex systems can be tested, simulated, predicted and monitored.

This thesis discusses various challenges, techniques and directions in modeling PV systems. Particular design considerations are required for PV systems. Atmospheric conditions have a massive influence on the performance and characteristics of a PV panel. The system used is based on VI (virtual instrumentation) technologies that empower researchers to consider high level software development tools for performance monitoring and modelling.

3.3 Objectives:

The objectives of thesis study are listed below.

- To develop a Model for PV systems on different platform that is capable of predicting the electric circuit parameters and analyzing the performance of the system.
- To use the model to study the effect of irradiance, ambient and cell temperatures and dust on the performance of PV panels

- To develop a monitoring PV system on different platform that is capable of online and automatic measurement and similarly tested for IV and PV curves under different environmental condition.
- To validate the model using experimental data and previously published work.

This work describes in detail the modeling approaches and challenges that are used for PV systems in a LabVIEW environments.

3.4 Thesis Approach:

The approach that is used to fulfill the objectives is comprised two major phases:

Modeling of PV system in LabVIEW software using the effects of environmental issues.

- The non-linear model of the PV panel using the five parameter equivalent electric circuit model is developed.
- Behavior of the PV panel output characteristics with respect to these parameters is investigated.
- Parameter values are estimated at Standard Test conditions (STC) to simulate the exact output characteristics of PV panel.
- LabVIEW model of the PV array is developed that is flexible enough to simulate any number of series and parallel connected panels.
- Robustness of the developed model is verified using simulation study at different operating conditions.

And monitoring and analysis of PV system in LabVIEW

- Develop a program to monitor on-line performance of the parameters of PV panel.
- Develop a program for measure and analyzing the performance using I-V and P-V curves under different conditions.
- The online and IV & PV data saved in Excel file for further investigations.

CHAPTER 4

MODELLING OF PV PANEL

4.1 Introduction

Basically, a photovoltaic cell is a p-n semiconductor that can be directly converted electricity. Naturally, PV devices exhibit nonlinear P-V and I-V characteristics that vary with cell temperature and radiation intensity. Ideally, a model consists of photo-generated current source and a diode. Mathematically, the ideal photovoltaic cell I-V characteristic describes from the theory of semiconductor as in equation (3):

$$I = I_{pv} - I_d = I_{pv} - I_o\left(e^{(\frac{qV}{akT})} - 1\right) \tag{3}$$

Where I_{pv} is photo-generated current (incident light generated current), I_d is Shockley diode current, Io is diode dark saturation current, T is cell temperature of p-n semiconductor junction, k is Boltzmann's constant (= $1.3806503*10^{-23}$J/K), q is charge of an electron (= $1.60217646*10^{-19}$C) and a is ideal factor of cell type that depends on PV technology.

4.2 Modelling:

In this chapter a generalized model of photovoltaic array is developed in the LABVIEW environment. The basic ideal equation of elementary photovoltaic cell is not representing a practical photovoltaic array I-V characteristic. Practical arrays consist of numerous connected and joined PV cells and characteristics observation at PV terminals requires additional parameters to include in ideal equation of the photovoltaic array. This model is designed based on the practical involving five parameters equivalent electric circuit. Parallel resistance mainly exists because of p-n junction leakage current. This model lies in the estimation of the model parameters which is the major challenge in implementation. To regenerate the output characteristics of PV panel accurately, the exact values of these parameters are required. One of the approach is introduced in [36] to identify the values of four parameters of a model at nominal condition Standard Test Condition (STC). The effectiveness of the developed model is investigated under different operating conditions. Results show that the proposed model can regenerate the I-V curves at nominal condition as well as at other operating condition with acceptable errors. Using simple Kirchhoff's current law on a single diode model following relationship can be found describe by equation (4)

$$I = I_{pv} - I_d - I_{sh} = I_{pv} - I_o (e^{(\frac{q(V+IR_s)}{akTN_s})} - 1) - \frac{(V+IR_s)}{R_p} \tag{4}$$

where $I_{o,}$ $I_{pv,}$ $I_{d,}$ I_{sh} and are the saturation current, photovoltaic current, diode current and shunt branch current respectively, of an PV panel. V and I represent the voltage and current generated from photovoltaic panel and Rp and Rs are the parallel and series resistance respectively and ‘a’ is ideality factor for diode and its value is between 1 to 2. Ns is series connected cells and Vt = kTNs/q which is PV array’s thermal voltage.

Modeling of photovoltaic devices is relatively complex due to transcendental non-linear characteristics of equation (4). Data generally supplied by the manufacturer have only few thermal and electrical characteristics experimental data. Basically datasheet provides the voltage-current pair values at open circuit, maximum power point (Vmp, Imp), short circuit and (Pmax) maximum power conditions at STC (1000 W/m^2 and 25^{0}C). Those parameters having unknown values and their dependence on the operating condition (temperature and irradiation) add more difficulty in modeling. The parameters that are not provided by manufacturer’s datasheets are required for adjusting PV panel models, such as ideality constant for diode, photo-generated current, diode saturation current, parallel and series resistances.

The photovoltaic devices I-V characteristics depend on external influences like cell temperature and radiation intensity and on internal characteristics such as Rs and Rp of device. The photo-generated current (I_{pv}) of photovoltaic (PV) cell directly depends on amount of charge carriers generated and influenced by the cell temperature and also linearly depend on the radiation intensity as describe by [50], [67], [68], [94] as equation (5):

$$I_{pv} = (I_{pvn} + K_i \Delta T)\frac{G}{G_n} \tag{5}$$

$$\Delta T = T - T_n \tag{6}$$

where $I_{pv,n}$ is photo-generated current at STC, T & T_n is actual and reference cell temperatures respectively, G is solar radiation intensity on surface of device and G_n is reference solar radiation. K_i is the cell short circuit current temperature coefficient.

In contrast, saturation current of diode Io varies with the cell temperature and may be expressed either of equation (7) and equation (9)

$$I_o = I_{on} \left(\frac{T}{T_n}\right)^3 e^{\left(\frac{qE_g}{ak}\left(\frac{1}{T_n} - \frac{1}{T}\right)\right)} \tag{7}$$

Where I_{on} is saturation current found by evaluating eq (3) at STC, V = V_{ocn}, I = 0, I_{pv} = I_{scn}:

$$I_{on} = \left(\frac{I_{scn}}{e^{\left(\frac{V_{ocn}}{aV_{tn}}\right)} - 1} \right) \tag{8}$$

With V_{tn} is thermal voltage at reference temperature, E_g is semiconductor band gap energy used in cell (approx 1.12eV). The value of a (diode ideality factor) may be randomly chosen, typically, $1 \leq a \leq 1.5$ and other parameters also depend on this choice of PV model.

$$I_o = \left(\frac{I_{scn} + K_i \Delta T}{e^{\left(\frac{V_{ocn} + K_v \Delta T}{aV_t}\right)} - 1} \right) \tag{9}$$

This equation (9) is obtained and differs by including the voltage and current coefficients K_v and K_i in equation (7). Thus, equation (9) expresses different approach that shows I_o

dependence on cell temperature. This results the linear variation effect on open-circuit voltage of cell temperature with respect to practical voltage temperature coefficient.

Two parameters R_s and R_p remain unknown and the photo-generated current (I_{pv}) is difficult to determine without the influence of parallel and series resistances. The assumption $I_{pv} \approx I_{sc}$ is usually used in photovoltaic modeling because of high parallel resistance and low series resistance practically.

A method defined in [19] is used for adjusting R_p and R_s based on the pair (R_s, R_p) that warranties that the experimental maximum power at MPP (V_{mp}, I_{mp}) from datasheet ($P_{max,e}$) is equal to I-V model calculated maximum power ($P_{max,m}$) i.e. $P_{max,e} = P_{max,m} = V_{mp}\ I_{mp}$ of I–V curve at the (V_{mp}, I_{mp}) point. By making $P_{max,e} = P_{max,m}$, the relation between R_s and R_p is establish as shown by equations (10) and (14)

$$P_{\max,m} = V_{mp}\left\{I_{pv} - I_o\left(e^{\left(\frac{V_{mp}+R_s I_{mp}}{aV_t}\right)} - 1\right) - \left(\frac{V_{mp}+R_s I_{mp}}{R_p}\right)\right\} = P_{\max,e} \tag{10}$$

$$R_p = \frac{V_{mp}(V_{mp}+I_{mp}R_s)}{\left\{V_{mp}I_{pv} - V_{mp}I_o e^{\left(\frac{V_{mp}+I_{mp}R_s}{aV_t}\right)} + V_{mp}I_o - P_{\max,e}\right\}} \tag{11}$$

These equations (10) and (14) makes I–V curve of model mathematically cross the experimental maximum power points (V_{mp}, I_{mp}) which means for a value of R_s there will be a unique value of R_p. The aim is to get the value of R_s and thus R_p that makes P-V curve peak of mathematical model coincide with peak experimental power at the (V_{mp}, I_{mp}) point.

To calculate the maximum power, equation (4) was solved for current for the entire range of voltages from 0 to the open circuit voltage V_{oc} and the maximum power was found by multiplying currents and voltages and searching for the maximum value. If the error of the predicted power from the experimental value were within the specified tolerance, the solution terminated otherwise the value for R_s was incremented and the process was repeated. This requires numerous iterations until $P_{max,e} = P_{max,m}$. Every iteration updates R_p and R_s towards the optimal model solution. The values of R_s and R_p are primarily unknown but after several iterations as solution refined the values of R_s and R_p tend to finest model solution. Thus I_{pv} photo-generated current is determined effectively by consideration the influence of parallel and series resistances of PV panel.

$$I_{pvn} = (R_p + R_s)\frac{I_{scn}}{R_p} \tag{12}$$

Initial guesses for Rs and Rp are required before the beginning of iterative process. The Rs initial value is zero and Rp initial value is given by

$$R_{p\,\min} = \frac{V_{mp}}{(I_{scn} - I_{mp})} - \frac{(V_{ocn} - V_{mp})}{I_{mp}} \tag{13}$$

This is actually a line segment (slope) between MPP and short circuit that determines the R_p minimum value. The series resistance controls the I-V characteristics curve slope at open circuit condition and impact the shape near MPP. Although $R_{p,min}$ is surely smaller than actual R_p thus this is better initial guess.

In iterative scheme, series resistance (R_s) should be increase slowly that adjusting the model curve of P–V towards experimental MPP data which requires a number of values of Rs and R_p for finding the best curve. Plotting the curves for I–V & P–V requires solving the basic equation (3) for voltage, $V \in [0,V_{oc,n}]$, and current, $I \in [0,I_{sc,n}]$. Direct solution is not possible from equation (3) because V = f(I,V) and I = f(V,I). Numerical method is used to solve this transcendental equation. By solving numerically $g(V,I) = I - f(V,I) = 0$, I-V points are obtained by obtaining the corresponding current (I) points for set of voltage (V) values. P–V points are obtained by multiplying corresponding I and V points.

Once all the five parameters are available the P-V and I-V characteristics curves could be drawn. With the aim of including cell temperature and solar irradiation dependence on V_{oc}, equation (4) is also solved using Newton-Raphson algorithm at I=0 and the result is found after few iterations.

CHAPTER 5

SYSTEM MEASUREMENT AND DEVELOPMENT

5.1 LabVIEW environment experimental set-up

The developed system is used to monitor and analyze a stand-alone photovoltaic system located at KFUPM campus, Dhahran, Saudia Arabia. This system is formed by two solar panels, environmental parameters and irradiation sensors, isolation amplifier, resistive load banks, amplifier circuit and data acquisition instrument (DAQ). The entire system is monitored and controlled by LabVIEW environment.

Figure 6 shows the block diagram of the stand-alone PV system experimental set-up. Each panel has a maximum power of 150 W, open circuit voltage of 43.2 V, short circuit current of 4.49 A, maximum power voltage of 36V and maximum power current of 4.16 A. All of these characteristics are under clean standard test condition of 1000 W/m^2 at 25° C. The panel has a length of 1580 mm, width of 808 mm and the actual irradiation exposed area of 1.5 m^2. The panels are installed and exposed to whole day sun irradiation and inclined at a fixed angle of 23° from horizontal surface. Two VelociCalc Plus devices having model number 8386A are used to measure weather parameters. The first one is dedicated to measure the ambient temperature, relative humidity and wind speed in the vicinity of both panels. The second device is fully dedicated to measure the panel temperature. These data are processed in VelociCalc Plus devices and transferred to CPU through serial RS232 connections after converting RJ45 to RS232. The continuous irradiation measurement is conducted using the RESOL device having model number solar cell CS10 type E sensor. The short circuit current of the irradiation cell measurement is amplified and processed through amplifier circuit. Each panel voltage and current are measured through LEYBOLD four channel highly linear, noise-immune isolating amplifiers model number [735 261]. The conditioned currents and voltages are channelled to LabVIEW environment through National instrument device DAQ NI USB-6251.

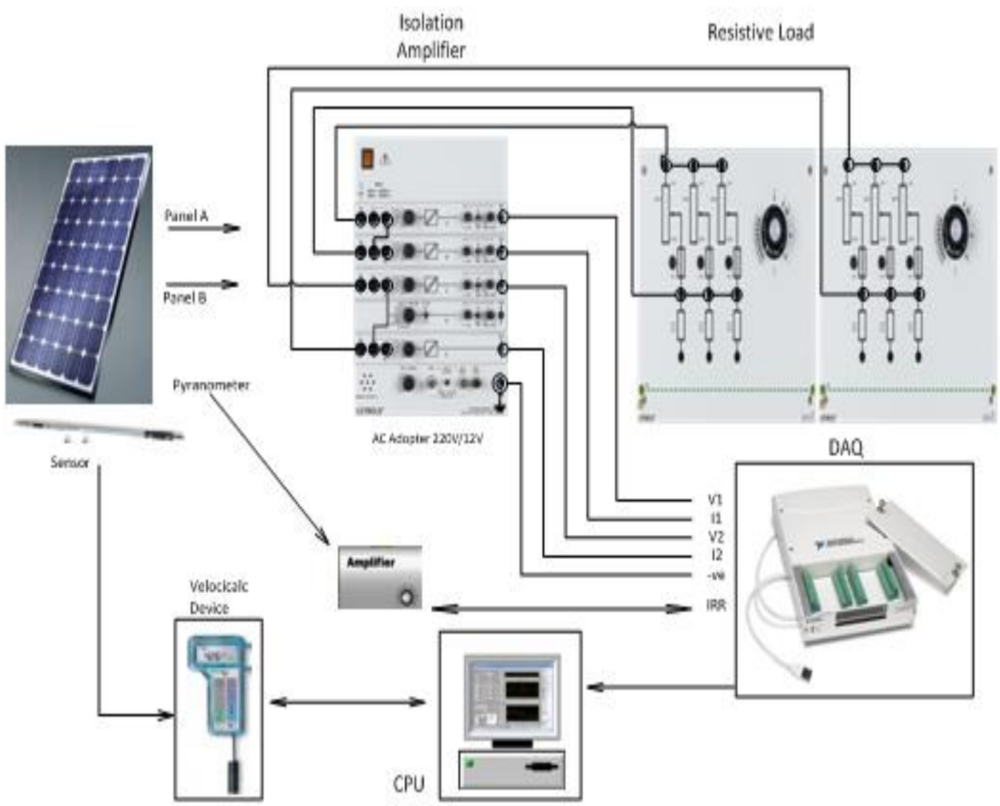


Figure 6: Block diagram of Labview system development

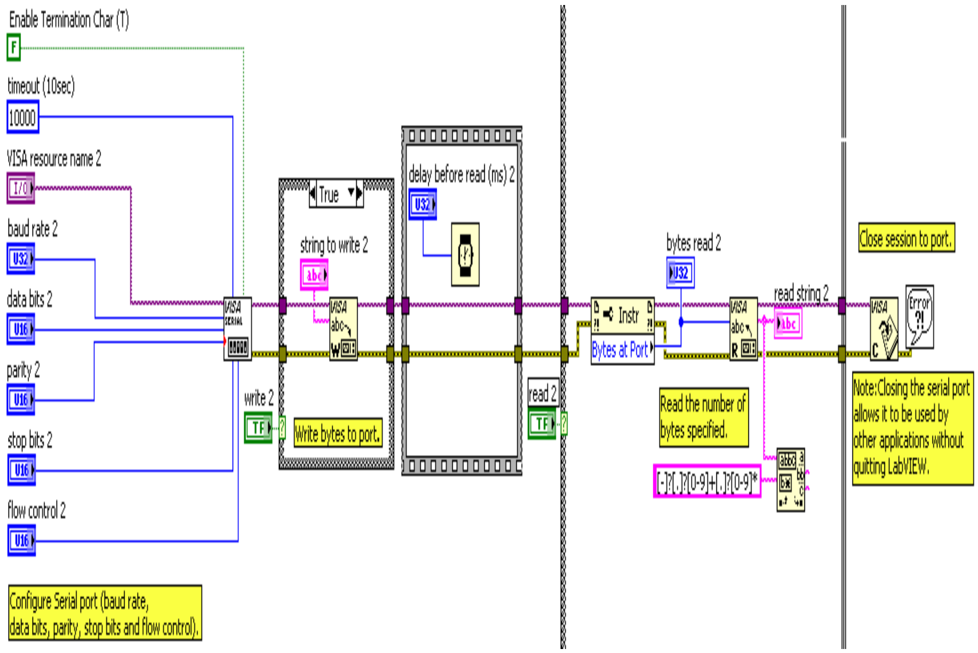
5.2 Labview Development

LabVIEW software manages communication between CPU and the I/O modules. Measurement & automation explorer (MAX) software tool is used for the configuration of data acquisition hardware device and the software. This tool creates tasks, channels, scales, interfaces and virtual instruments. The serial instrument or device includes software utilities and hardware drivers for communication, and also includes the documentation on the stop bits, parity bits, baud rates, and packet size that the instrument used.

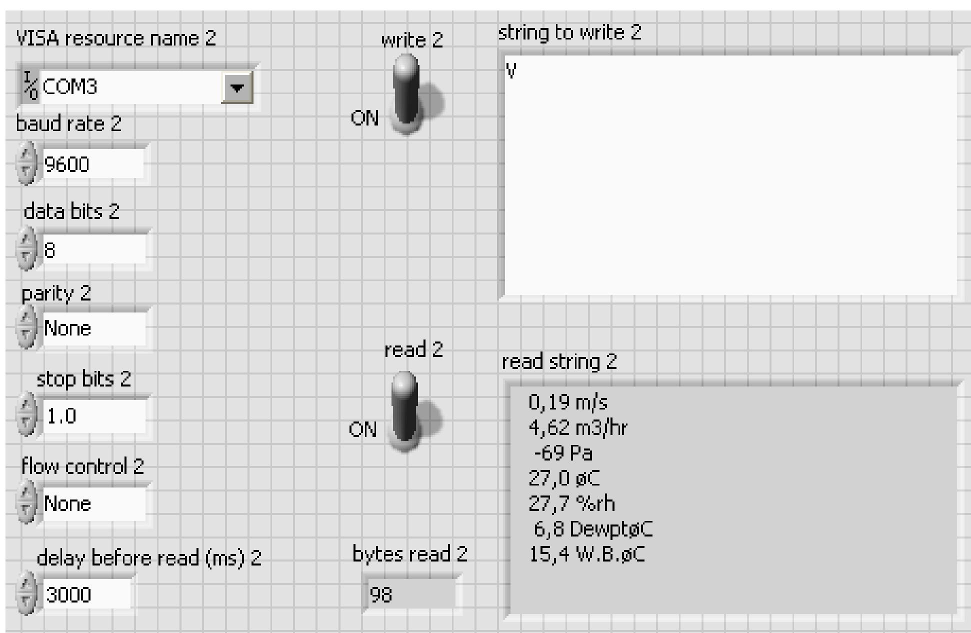
In LabVIEW programming, computer processors can execute the code when the graphical icons are joined and wired together, and then directly compiled to machine code. A block diagram functions in the data flow path that actually dictates when and in what order the program will execute. All inputs data must be available at a node for execution, and then it carries out data to its output and supplies to the next node in the path. We also used Express VIs (Virtual Instrument) that simplifies common programming tasks and algorithm creation. DAQ Assistant Express VI is used on the block diagram and configures it to execute the function. The DAQ Assistance Express VI prompts you to select the channels you want to send and receive data to I/O module (DAQ), and configure parameters like terminal configuration, scales, sample rate, triggering, and synchronization. After completing the configuration, the LabVIEW development environment writes the necessary code (represented by the Express VI) for you which actually is the task of reading real outer signals into inner files for analysis.

In the front panel we configure and customize the control parameters to communicate with serial port and in the block diagram window we connect the blocks for serial connection. To perform the serial communication task, VISA resource is opened and configures COM port. VI will then first write command V for data, read data and then close the VISA session that opened to port for every specified reading cycle. A specific command is written and sends to the device then the response is read back. VI will then wait if the reading is performed until the specified number of bytes is received at the port. Figure 7(a) shows the developed graphical programming block diagram and Figure 7(b) shows the corresponding front panel control area.

Data received from the device are in string format which needs to be processed for display and storage. The module is developed as shown in Figure 8. It is designed to segregate, concatenate and then arrange the entire data in an array form. The resultant values are then joined to make an array and a table for continuous reading and monitoring. The data is then saved to a excel file. Graphs and charts are used to display plots of data in a graphical form. The outcome of this developed module leads to the segregated environmental parameters namely; wind speed, humidity, ambient temperature and panel temperature.



(a) Block diagram



(b) Front panel

Figure 7: Serial Communication in LabVIEW: (a) Block diagram and (b) Front panel

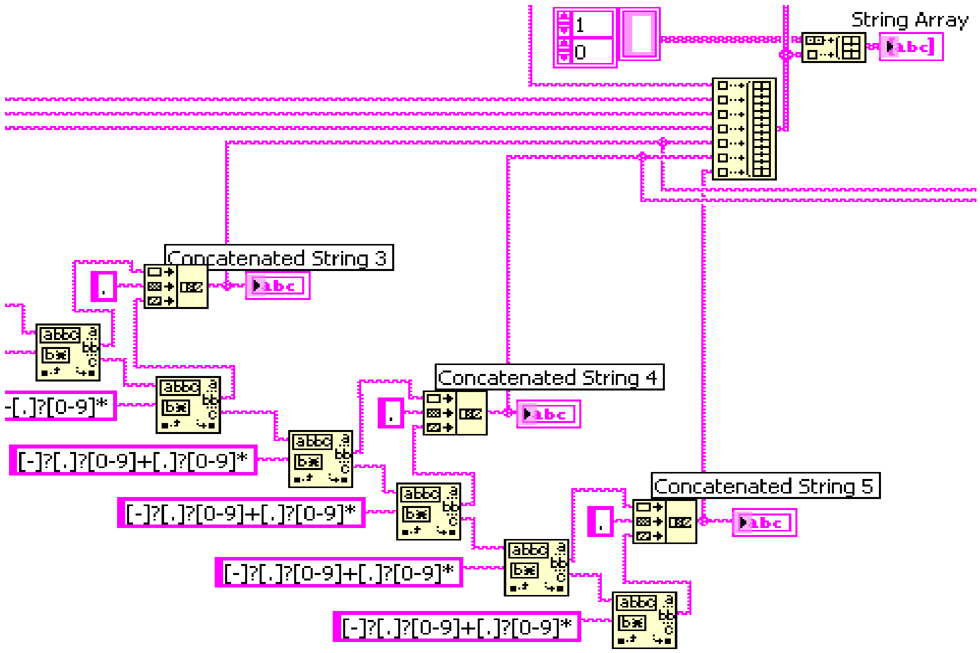


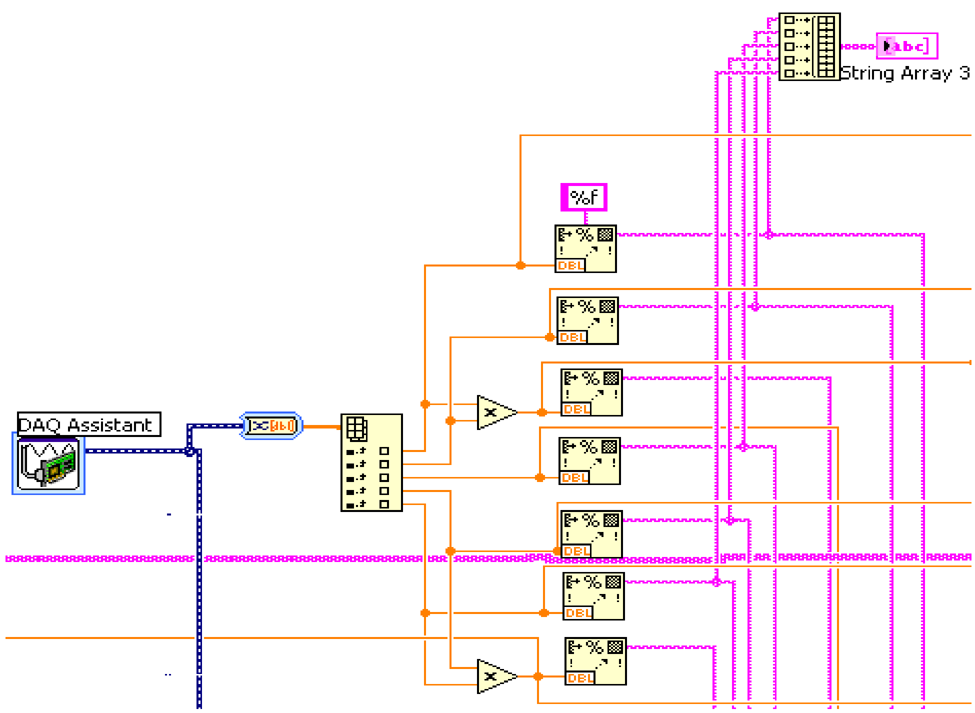
Figure 8: Data conditioning for analysis, displaying and storage.

Figure 9(a) shows LabVIEW data processing path coming from the data acquisition system through the Express DAQ Assistant. The VI allows to setup different channels for parameters with scaling factor and corresponding calibration of each channel. The instantaneous values of all variables like voltages, currents and irradiation could then be processed, analyzed, used for online control, online display and storage. Figure 9(b) shows the developed module for taking a mean value of a certain specified time interval for any desired variable.

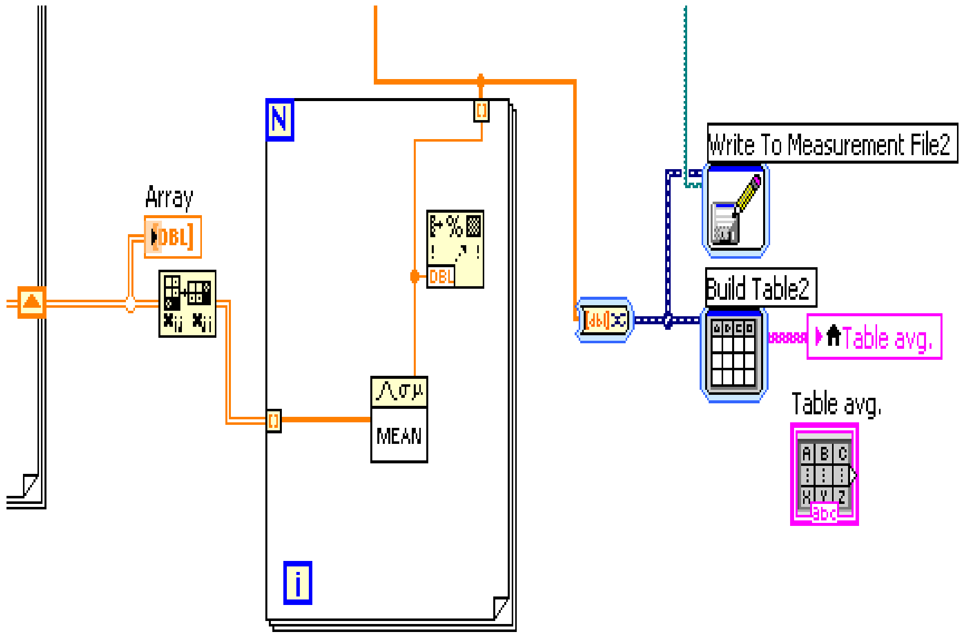
The voltage and current points are taken and captured along the I–V curve starting from open circuit load to short circuit load. The subsequent P-V curve points are captured simultaneously while the load resistance is being varied. The corresponding block diagram is shown in Figure 10. This module is based on the corresponding front panel manual control button for data collection. I and V data are measured and P is calculated.

The data points are collected in an array and then converted to dynamic format in order to build the corresponding X and Y axis. The I-V and P-V curves are displayed on the front panel directly. The subsequent stage is the module to super-impose the next I-V and P-V curve. Finally the corresponding I-V and P-V data are stored in a measurement file.

The front panel of the developed virtual instrument depicts graphics and numerical data of all parameters and variables. The data are stored in the measurement file and in Excel format. All stored information is based on instantaneous and mean values. When the block diagram has a branch or node, then the code is executed in parallel automatically and managed by LabVIEW filters. Thus parallel nature makes multitasking and multithreading simple to implement.



(a) DAQ Assistant data processing



(b) Averaging of all parameters

Figure 9: Developed program for: (a) DAQ Assistant data processing (b) Averaging of all parameters

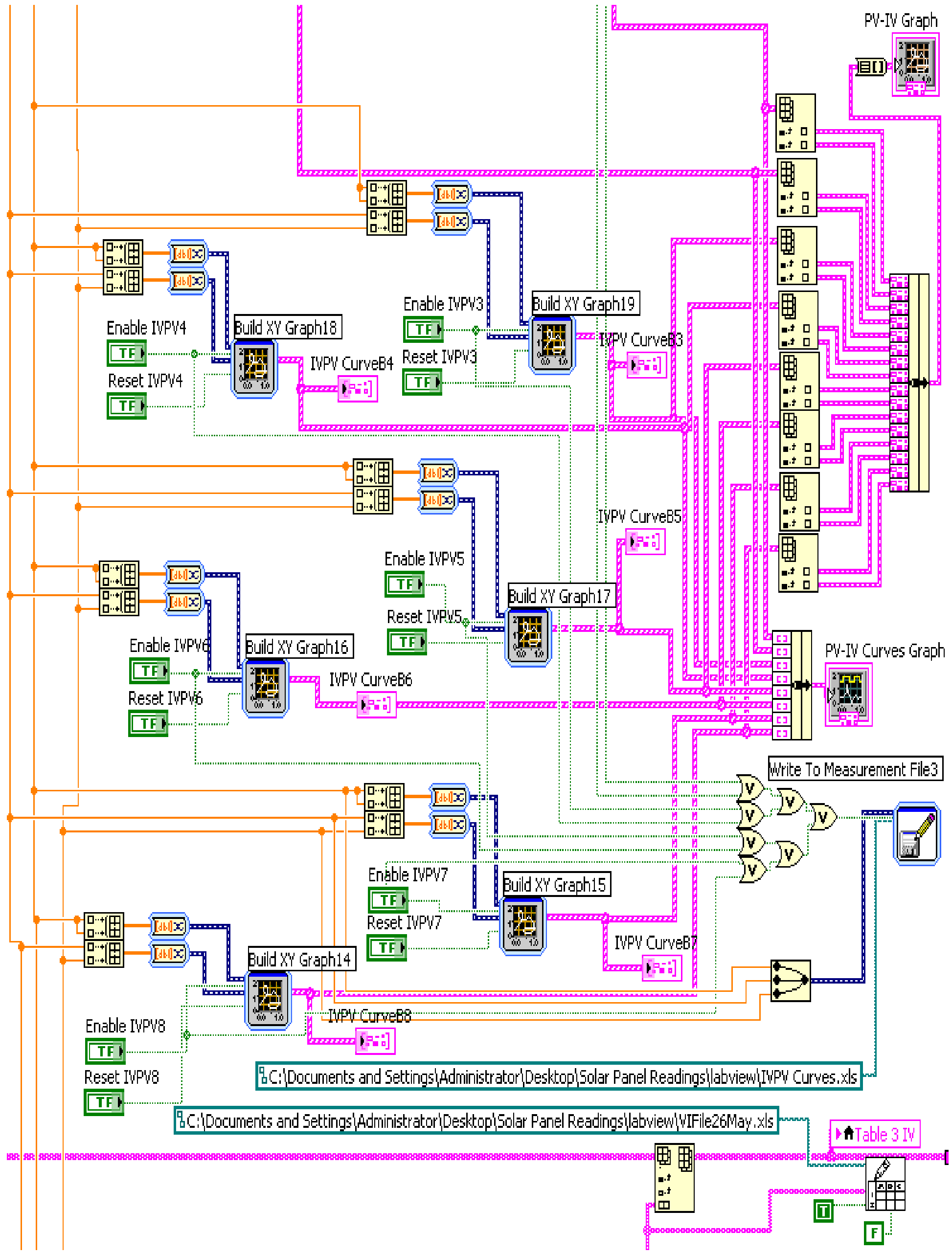


Figure 10: Developed module for I-V and P-V curves

CHAPTER 6

DATA ANALYSIS

6.1 Environmental condition impact on PV panel resistances:

The environmental parameters such as ambient temperature, irradiation, humidity, dust, wind speed have major impact on PV performance. The IV curve of the PV panel reflects its performance for all loading level at specific panel temperature and solar irradiation. The method applied to reach the IV at any environments condition consists of fast variation of the load resistance from a very high value (open circuit) to a zero resistance (short circuit) passes by the maximum power point. Rp and Rs are respectively the parallel and series resistance. Figure 11 shows the corresponding slopes relevant to each resistance. Equation 14 and equation 15 describes the slope of resistances.

$$\frac{\Delta V_s}{\Delta I_s} = R_s \tag{14}$$

$$\frac{\Delta V_p}{\Delta I_p} = R_p \tag{15}$$

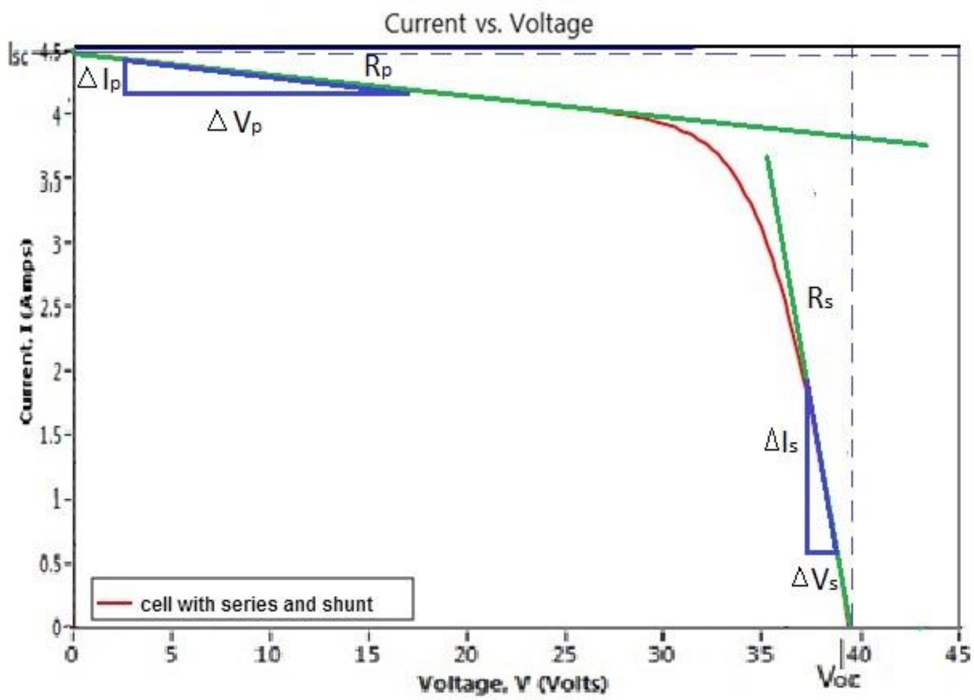


Figure 11: Slopes of Rp and Rs

The objective is to reach the values of Rp and Rs under environmentally changing conditions. The study area experience extreme weather changing parameter such as high temperature, frequent dust storm and regular high range of irradiation, high humidity level and rare air movement. For this purpose two different methods, model estimation parameter and iteration analysis of the parameter estimation method are carried out. The data gives the Rs and Rp values of I-V pair at practical short-circuit current (Isc), open-circuit voltage (Voc) and maximum power point conditions (Vm, Im) at given temperature and irradiation. To carry out this study, the I-V curves generated by estimated parameters are compared with the experimental curves. Figure 12 shows ten experimental I-V curves (green) with corresponding simulation I-V cures (red) are super imposed in one graph for analysis and determination of Rp and Rs values.

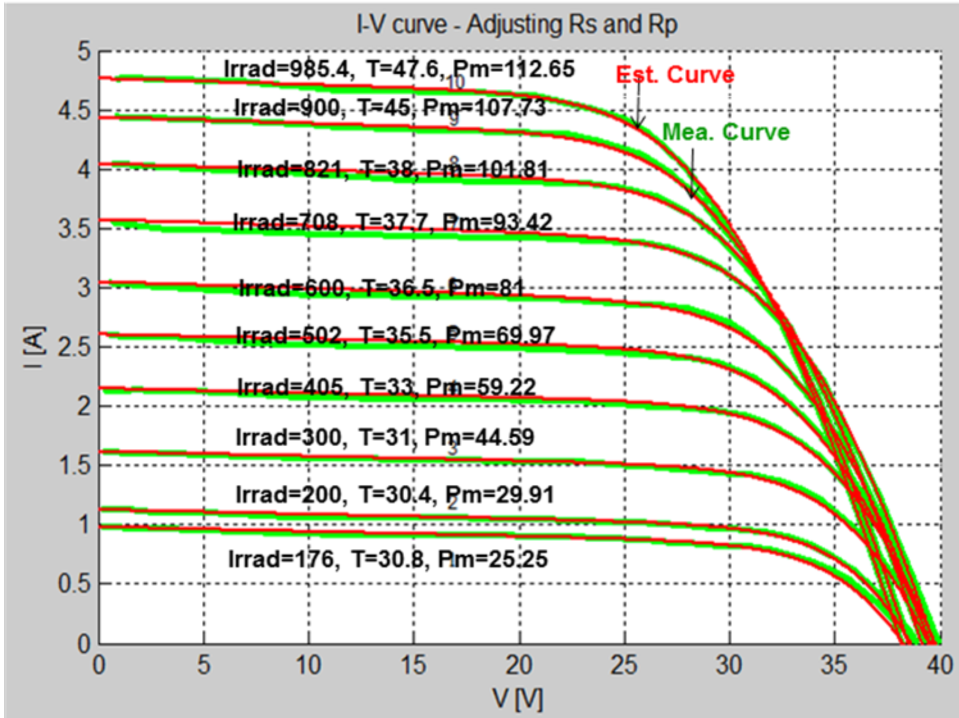


Figure 12: Experimental & manual IV curves for clean PV panel

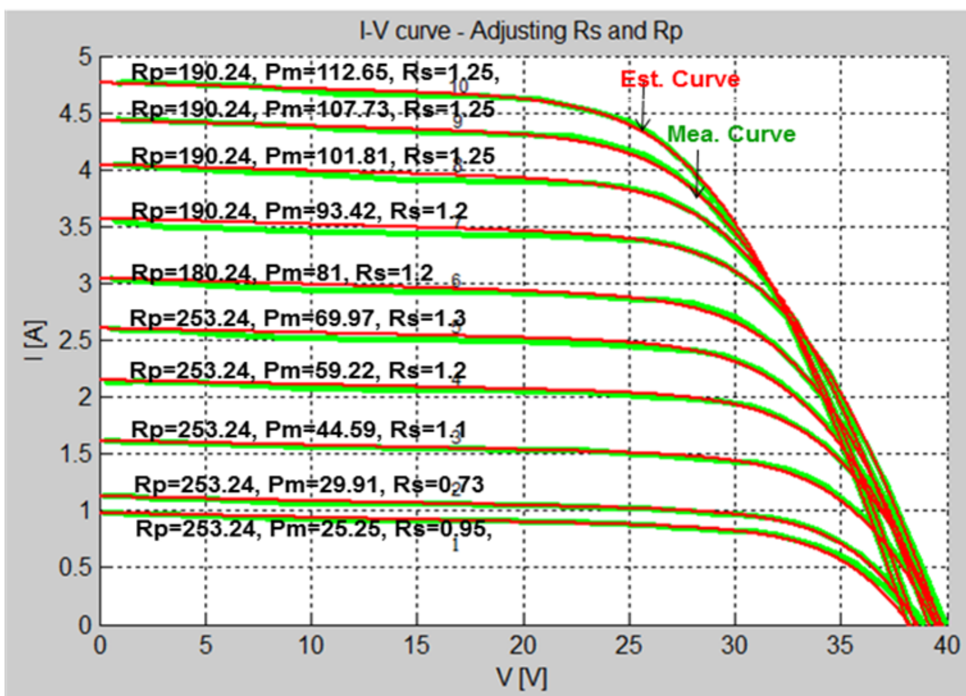


Figure 13: Rp and Rs on IV curves for clean PV panel

Result and analysis show that these methods can simulate the output characteristics of photovoltaic efficiently. Series resistance (Rs) has a central job in finding the curvature of the I-V curve as shown and its large value depicts a smoother curvature which is a usual behavior of Ideality of I-V curves. The electrical characteristics of clean PV panels are simulated using the estimated parameters and this approach is validated by comparing the determined curves (generated by estimated parameters) with the experimental curves of a clean PV panel. The experimental curves data are extracted from the excel sheet of installed PV panel using Matlab software. Figure 12 shows the determined I-V curves (red color lines) along with the experimental curves (green colour) of a clean PV panel for different irradiation level and cell temperatures. Figure 13 shows the values of Rp and Rs of I-V curves of clean PV panel. It illustrates that the I-V curves obtained from these method are in great accordance with the experimental curves.

The results are summarized in Table 1 (07Oct13). Similarly, Table 1 also shows the comparison of modeled and experimental I-V curves for clean PV panel. It can be seen that the curves generated from these method matches with the experimental curves.

To find the dust effect on Rs and Rp of PV panel, we analyze different cases having two days dusty panel, one week, two weeks, three weeks, four weeks dusty panels and also by putting measured dust on PV panel. Following figures shows the determined I-V curves (red color lines) along with the experimental curves (green colour) of a dusty PV panels for different irradiation level and cell temperatures.

Table 1 Summary of IV curve for clean PV panel

No.	Time AM	Temp (Amb) (°C)	Temp (Cell) (°C)	Irrad (W/m²)	Voc (V)	Isc (A)	Pm (W)	Iterative method		Model method	
								Rs (Ω)	Rp (Ω)	Rs (Ω)	Rp (Ω)
1	6:12	30.4	30.8	176	38.65	0.98	25.25	0.95	253.24	0.95	253.24
2	6:17	27.5	30.4	200	38.95	1.125	29.91	0.73	253.24	0.48	263.16
3	6:32	29.8	31	300	39.7	1.615	44.59	1.1	253.24	0.4	219.53
4	6:51	31.1	33	405	39.95	2.148	59.22	1.2	253.24	1.2	263
5	7:08	32.3	35.5	502	39.7	2.6	69.97	1.3	253.24	1.24	262.27
6	7:29	33.3	36.5	600	39.7	3.045	81	1.2	180.24	1.275	277.66
7	7:57	33.2	37.7	710	39.85	3.575	93.42	1.2	190.24	1.3	240.8
8	8:28	34	39.4	815	39.25	4.04	101.8	1.25	190.24	1.27	193
9	9:03	35.6	45	900	38.6	4.434	107.7	1.25	190.24	1.27	210
10	10:10	39.25	47.6	985	38.25	4.755	112.7	1.25	190.24	1.26	190.14

For case 1: Figure 14 illustrates the determined I-V curves (red color lines) along with the experimental curves (green colour) of a two days dusty PV panels for different irradiation level and cell temperatures. Figure 15 shows the values of Rp and Rs on I-V curves. Rp decreases with the increase of irradiation as shown in Figure 16. The results are summarized in Table 2 (09Oct13).

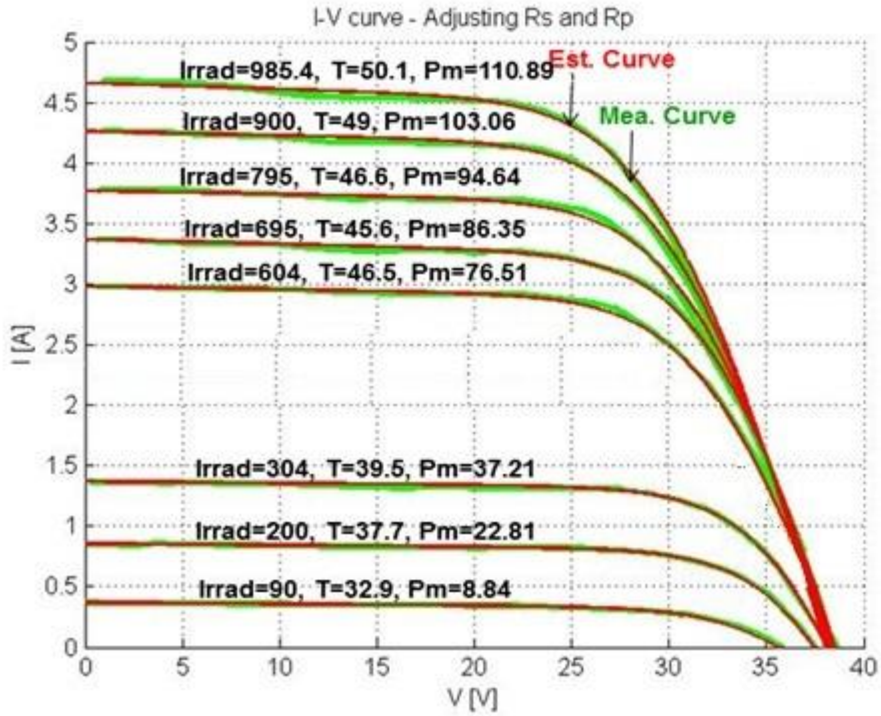


Figure 14: Experimental & manual IV curves for 2 days dusty PV panel

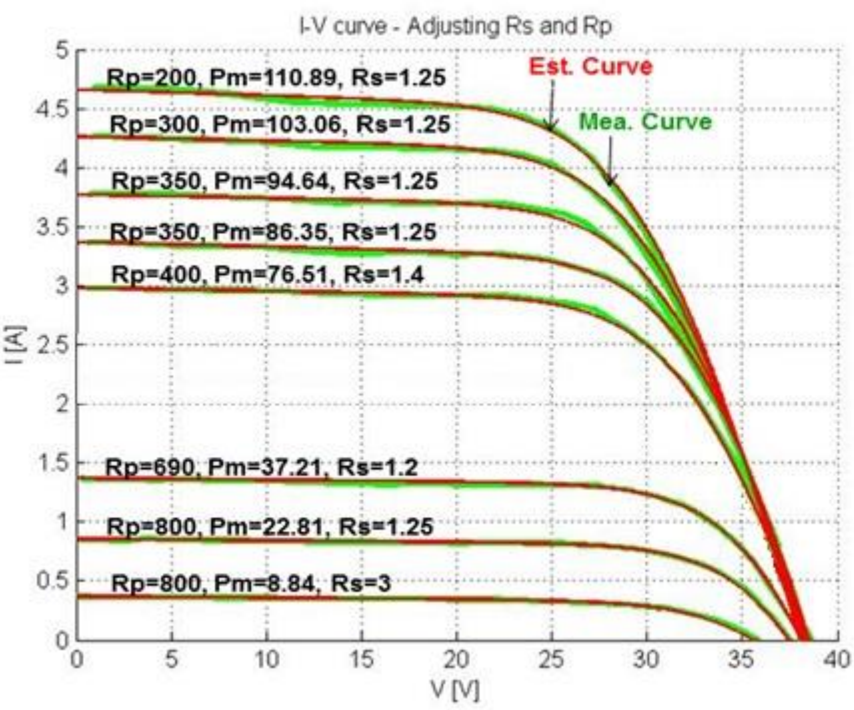


Figure 15: Rp and Rs on IV curves for 2 days dusty PV panel

Table 2 Summary of IV curve for 2-days dusty PV panel

No.	Time	Temp (Cell) (°C)	Irrad (W/m^2)	Eff. Irrad (W/m^2)	Voc (V)	Isc (A)	Pm (W)	Dust Index	Iterative method	
									Rs (Ω)	Rp (Ω)
1	3:31 PM	32.9	90	75	35.85	0.37	8.84	0.8333	3	800
2	3:15 PM	37.7	200	172	37.55	0.86	22.81	0.86	1.25	800
3	2:47 PM	39.5	300	275	38.2	1.37	37.21	0.9167	1.2	690
4	1:26 PM	46.5	605	590	38.55	2.98	76.51	0.9752	1.4	400
5	1:01 PM	45.6	700	674	38.6	3.37	86.35	0.9629	1.25	350
6	12:38 PM	46.6	795	754	38.45	3.77	94.64	0.9484	1.25	350
7	11:55 AM	49	900	852	38.25	4.26	103.06	0.9467	1.25	300
8	11:09 AM	50.1	985	932	38.15	4.66	110.89	0.9462	1.25	200

For case 2: Figure 17 illustrates the determined I-V curves (red color lines) along with the experimental curves (green colour) of one week dusty PV panels for different irradiation level and cell temperatures. Figure 18 shows the values of Rp and Rs on I-V curves. The behavior of Rp is same and decreases with the increase of irradiation as shown in Figure 19. The results are summarized in Table 3 (12Oct13).

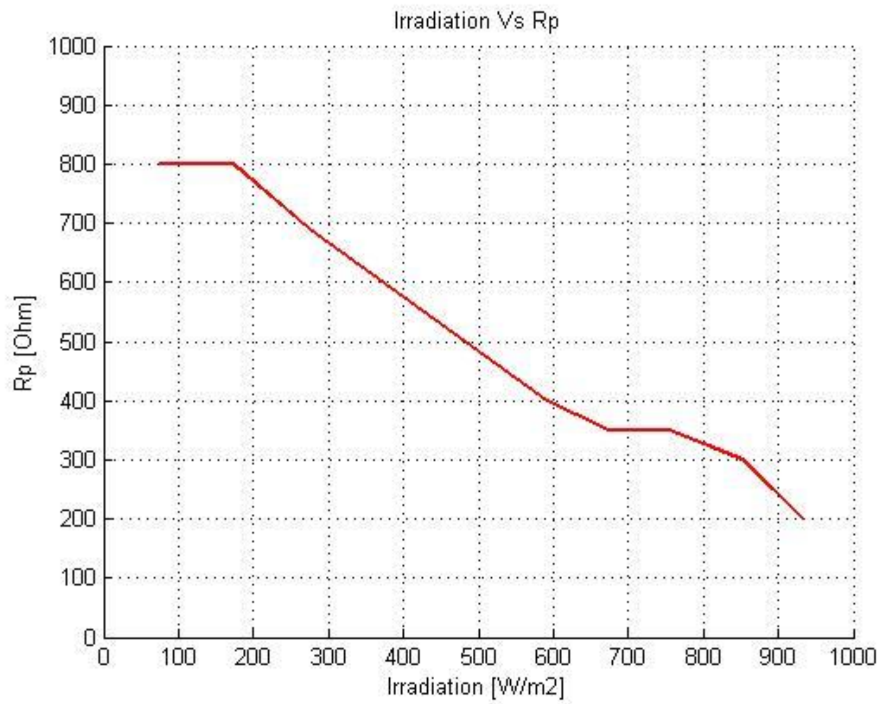


Figure 16: Effect of Irradiation in Rp for 2 days dusty PV panel

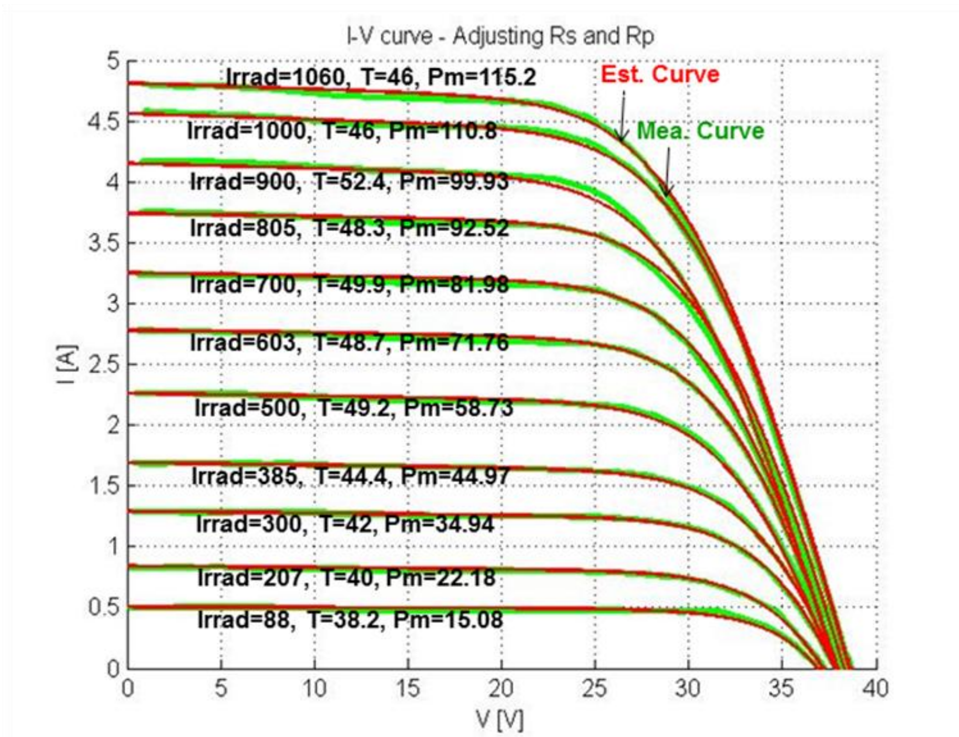


Figure 17: Experimental & Manual IV curves for 1 week dusty PV panel

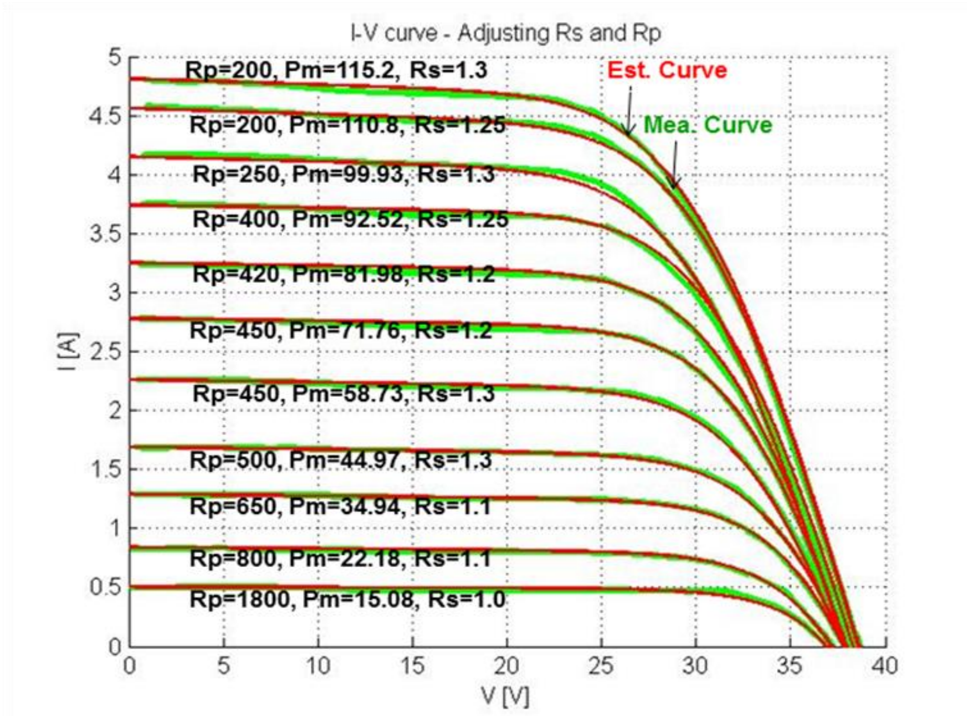


Figure 18: Rp and Rs on IV curves for 1 week dusty PV panel

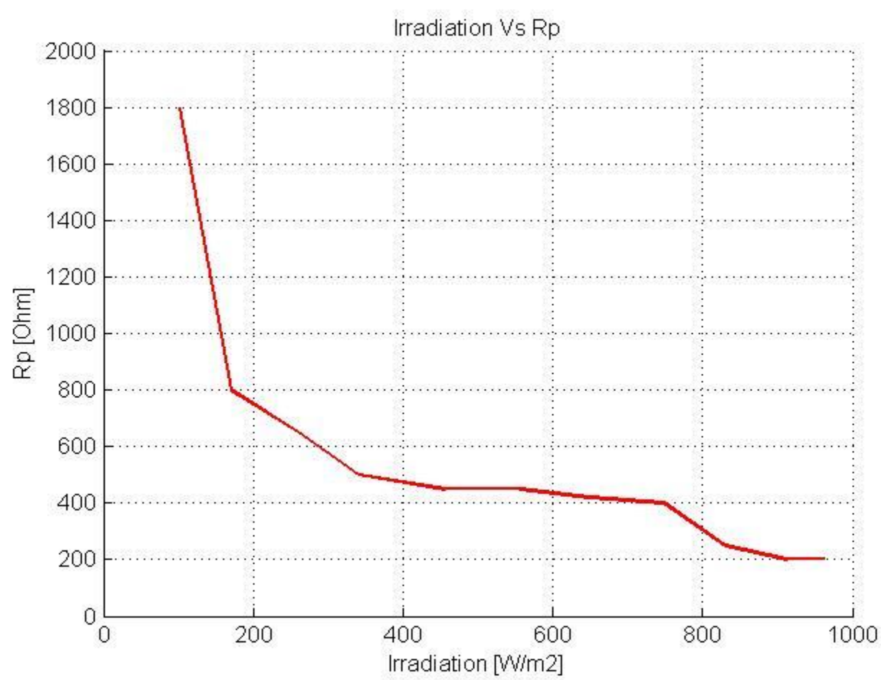


Figure 19: Effect of Irradiation in Rp for 1 week dusty PV panel

Table 3 Summary of IV curve for 1-week dusty PV panel

No.	Time	Temp (Cell) (°C)	Irrad (W/m²)	Eff. Irrad (W/m²)	Voc (V)	Isc (A)	Pm (W)	Dust Index	Iterative method	
									Rs (Ω)	Rp (Ω)
1	3:29 PM	38.2	88	101	36.95	0.51	15.08	1.1477	0.1	1800
2	3:11 PM	40	200	170	37.3	0.84	22.18	0.85	1.1	800
3	2:47 PM	42	300	260	37.9	1.29	34.94	0.8667	1.1	650
4	2:26 PM	44.4	385	340	38.05	1.69	44.97	0.8831	1.3	500
5	1:56 PM	49.2	500	455	37.85	2.26	58.73	0.91	1.3	450
6	1:29 PM	48.7	603	556	38.05	2.78	71.76	0.9221	1.2	450
7	1:04 PM	49.9	700	650	38	3.25	81.98	0.9286	1.2	420
8	12:37 PM	48.3	805	748	38.35	3.74	92.52	0.9292	1.25	400
9	11:58 AM	52.4	900	830	37.9	4.15	99.93	0.9222	1.3	250
10	11:23 AM	46	1000	912	38.65	4.56	110.8	0.912	1.25	200
11	10:37 AM	46	1055	962	38.7	4.81	115.2	0.9118	1.3	200

For case 3: Figure 20 illustrates the determined I-V curves (red color lines) along with the experimental curves (green colour) of a two weeks dusty PV panels for different irradiation level and cell temperatures. Figure 21 shows the values of Rp and Rs on I-V curves. The behavior of Rp is same and decreases with the increase of irradiation as shown in Figure 22. The results are summarized in Table 4 (21Oct13).

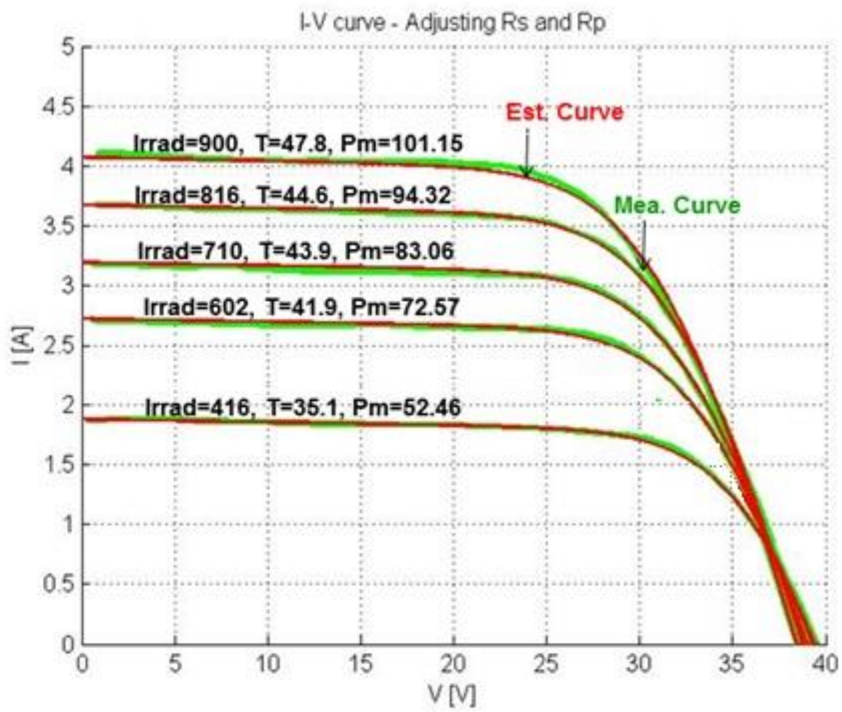


Figure 20: Experimental and manual IV curves for 2 weeks dusty PV panel

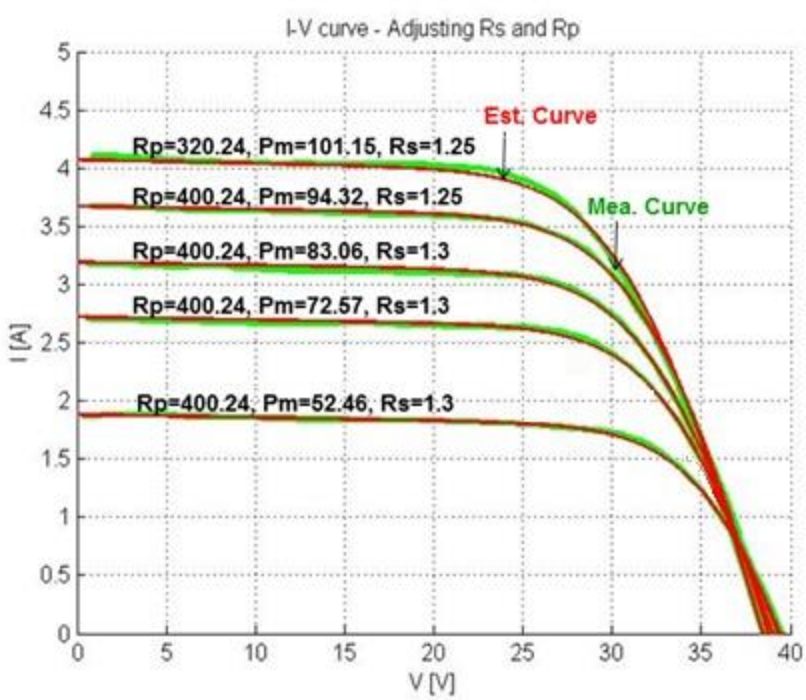


Figure 21: Rp and Rs on IV curves for 2 weeks dusty PV panel

Table 4 Summary of IV curve for 2-weeks dusty PV panel

No.	Time	Temp (Cell) (°C)	Irrad (W/m²)	Eff. Irrad (W/m²)	Voc (V)	Isc (A)	Pm (W)	Dust Index	Iterative method	
									Rs (Ω)	Rp (Ω)
1	7:03 AM	35.1	415	376	39.55	1.88	52.46	0.906	1.3	400
2	7:42 AM	41.9	602	544	39.1	2.72	72.57	0.903	1.3	400
3	8:07 AM	43.9	704	638	38.9	3.19	83.06	0.906	1.3	400
4	8:39 AM	44.6	815	734	38.8	3.67	94.32	0.900	1.25	400
5	9:22 AM	47.8	900	814	38.5	4.07	101.15	0.904	1.25	320

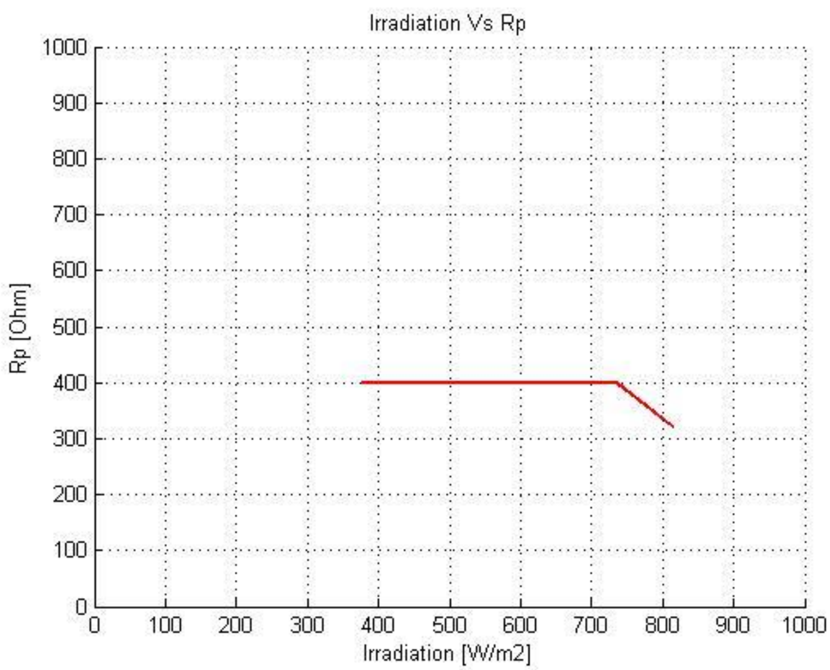


Figure 22: Effect of Irradiation in Rp for 2 week dusty PV panel

For case 4: Figure 23 illustrates the determined I-V curves (red color lines) along with the experimental curves (green colour) of a three weeks dusty PV panels for different irradiation level and cell temperatures. Figure 24 shows the values of Rp and Rs on I-V curves. The behavior of Rp is same and decreases with the increase of irradiation as shown in Figure 25. The results are summarized in Table 5 (31Oct13).

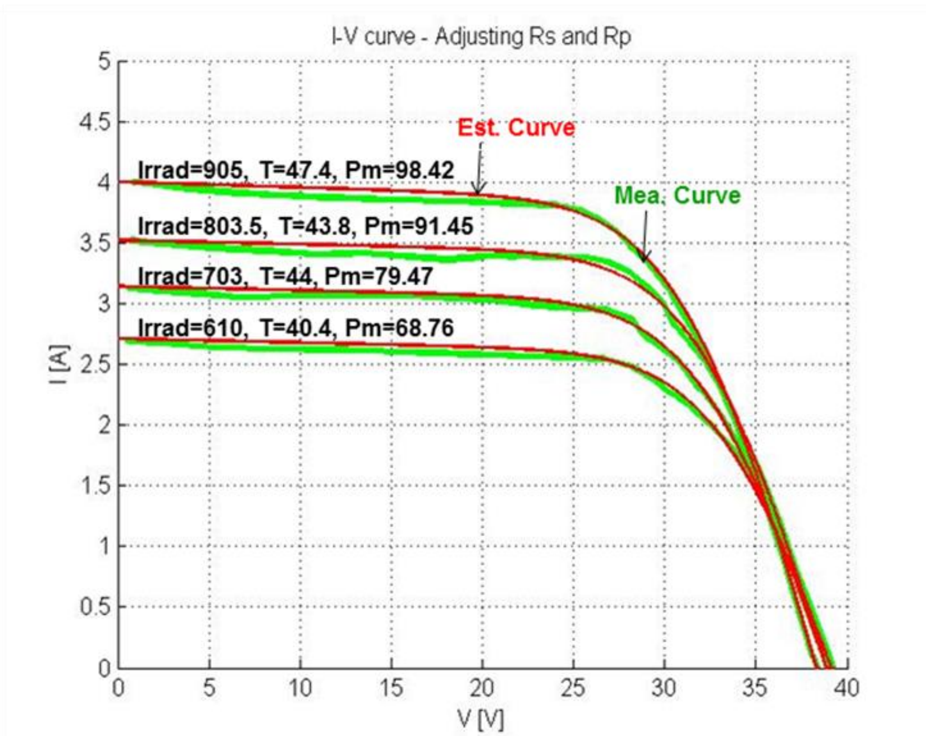


Figure 23: Experimental and manual IV curves for 3 weeks dusty PV panel

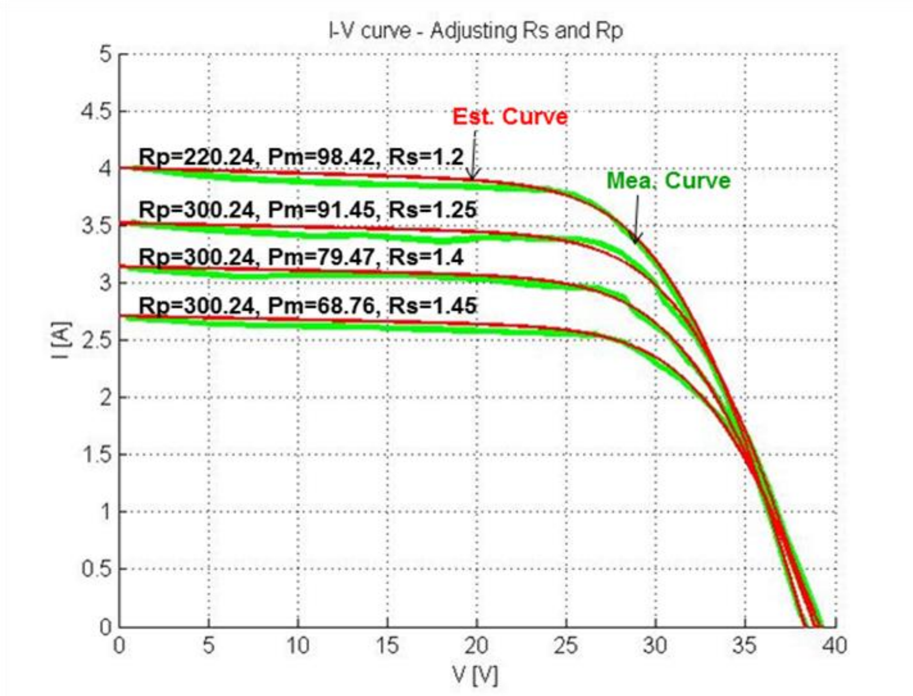


Figure 24: Rp and Rs on IV curves for 3 weeks dusty PV panel

Table 5 Summary of IV curve for 3-weeks dusty PV panel

No.	Time	Temp (Cell) (°C)	Irrad (W/m²)	Eff. Irrad (W/m²)	Voc (V)	Isc (A)	Pm (W)	Dust Index	Iterative method	
									Rs (Ω)	Rp (Ω)
1	7:34 AM	40.4	610	540	39.25	2.71	68.76	0.8852	1.45	300.24
2	8:12 AM	44	700	625	38.95	3.14	79.47	0.8929	1.4	300.24
3	8:28 AM	43.8	800	705	38.95	3.52	91.45	0.8813	1.25	300.24
4	9:18 AM	47.4	905	800	38.4	4.01	98.42	0.884	1.2	220.24

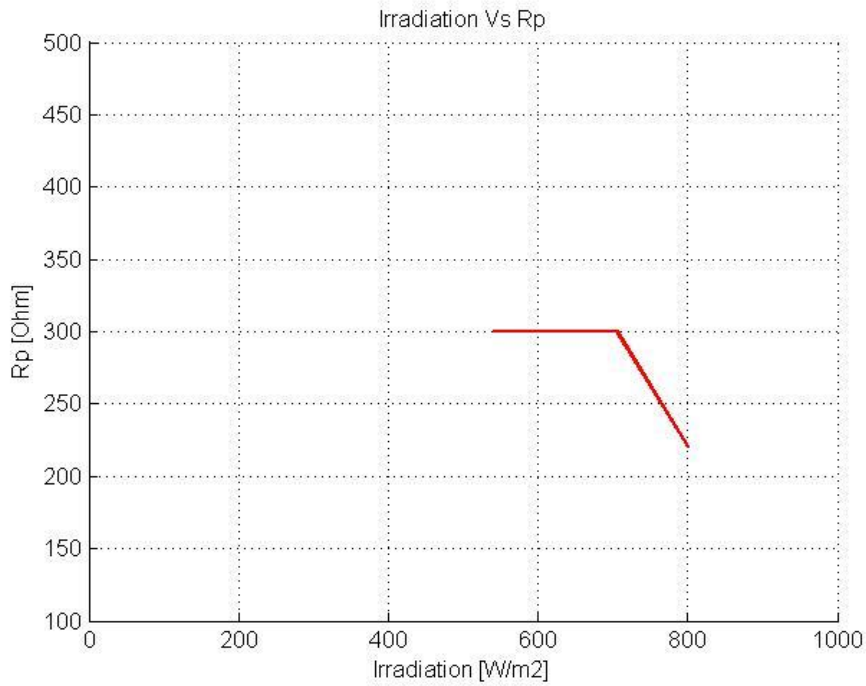


Figure 25: Effect of Irradiation in Rp for 3 weeks dusty PV panel

For case 5: Figure 26 illustrates the determined I-V curves (red color lines) along with the experimental curves (green colour) of a month dusty PV panels for different irradiation level and cell temperatures. Figure 27 shows the values of Rp and Rs on I-V curves. The behavior of Rp is same and decreases with the increase of irradiation as shown in Figure 28. The results are summarized in Table 6 (06Oct13).

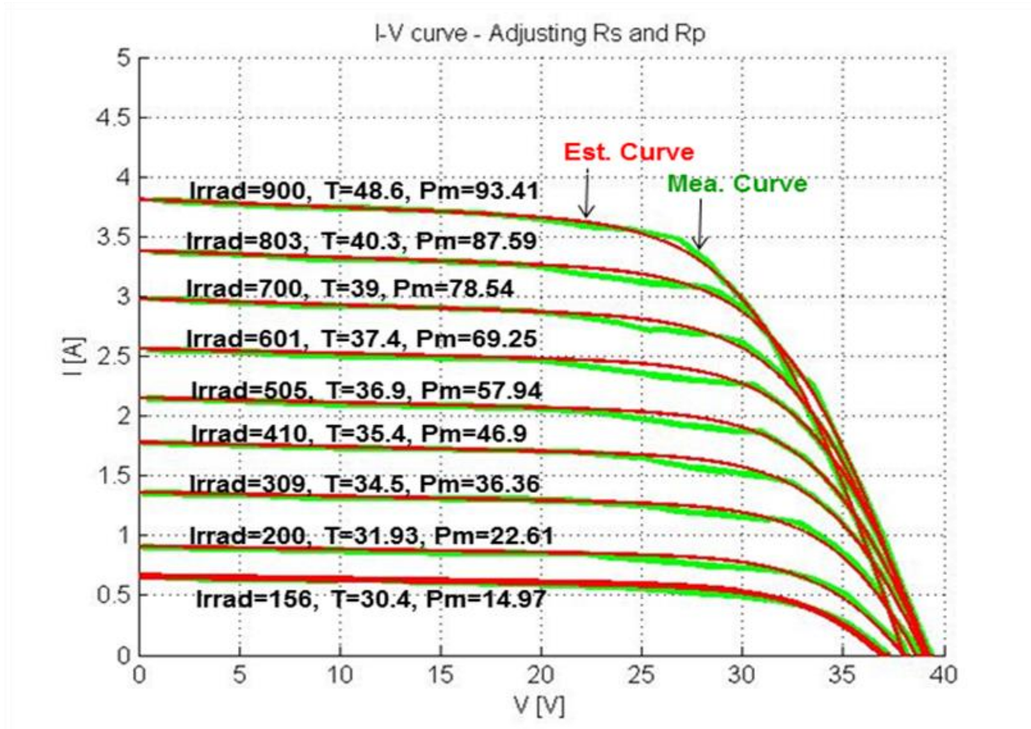


Figure 26: Experimental and manual IV curves for 1 month dusty PV panel

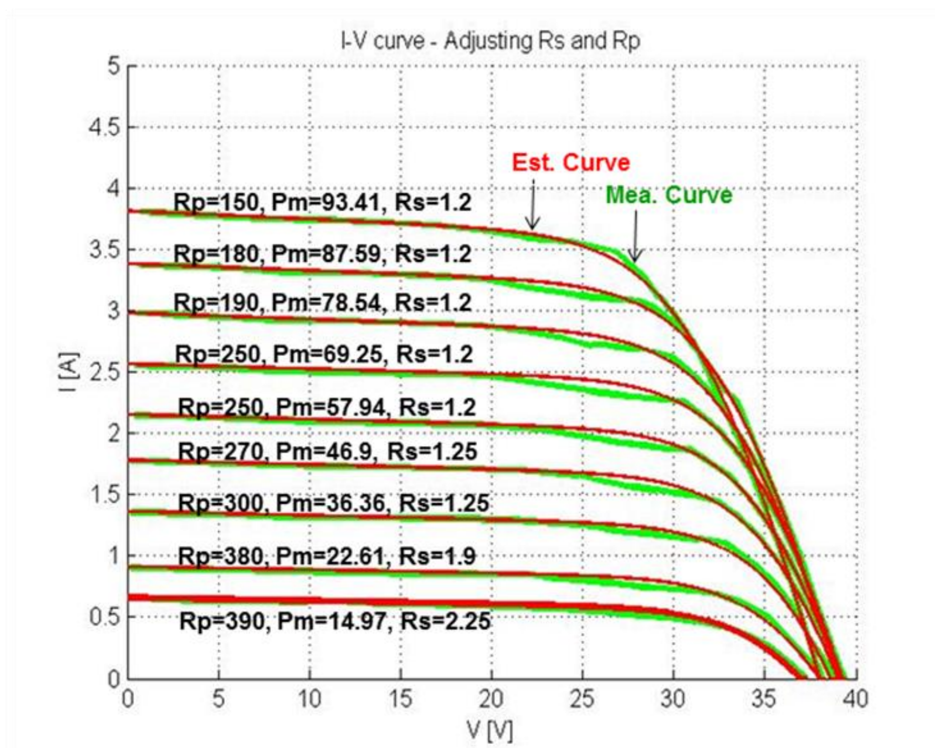


Figure 27: Rp and Rs on IV curves for 1 month dusty PV panel

Table 6 Summary of IV curve for 1-month dusty PV panel

No.	Time	Temp (Cell) (°C)	Irrad (W/m²)	Eff. Irrad (W/m²)	Voc (V)	Isc (A)	Pm (W)	Dust Index	Iterative method	
									Rs (Ω)	Rp (Ω)
1	6:13 AM	30.66	156	132	37.3	0.66	14.97	0.846	2.25	390
2	6:25 AM	31.93	205	180	38.25	0.912	22.61	0.878	1.9	380
3	6:43 AM	34.5	310	270	38.85	1.362	36.36	0.871	1.25	300
4	7:01 AM	35.4	410	356	39.2	1.78	46.9	0.868	1.25	270
5	7:19 AM	36.9	503	430	39.3	2.152	57.94	0.855	1.2	250
6	7:41 AM	37.4	602	512	39.4	2.563	69.24	0.85	1.2	250
7	8:05 AM	39	700	596	39.2	2.98	78.54	0.851	1.2	190
8	8:39 AM	40.3	803	676	39.15	3.38	87.59	0.842	1.2	180
9	9:20 AM	48.6	900	762	38.15	3.81	93.41	0.847	1.2	150

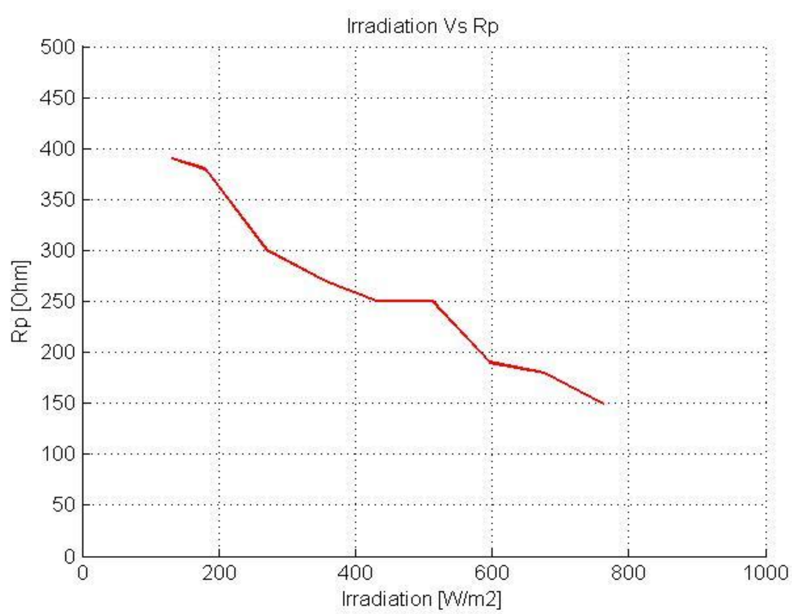


Figure 28: Effect of Irradiation in Rp for 1 month dusty PV panel

For case 6: Figure 29 illustrates the determined I-V curves (red color lines) along with the experimental curves (green colour) of a measured dusty PV panels for different irradiation level and cell temperatures. The 27.73g of dust is distributed over the PV panel. Figure 30 shows the values of Rp and Rs on I-V curves. The behavior of Rp is same and decreases with the increase of irradiation as shown in Figure 31. The results are summarized in Table 7 (20Feb14).

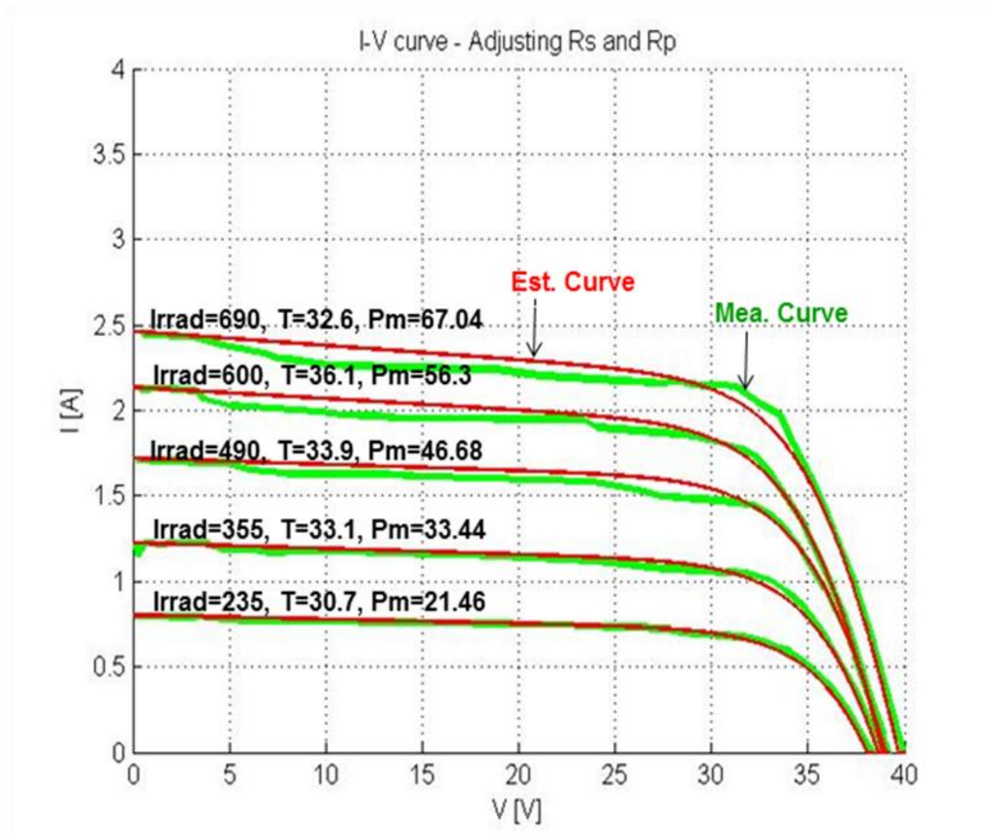


Figure 29: Experimental and manual IV curves for 27.73g dusty PV panel

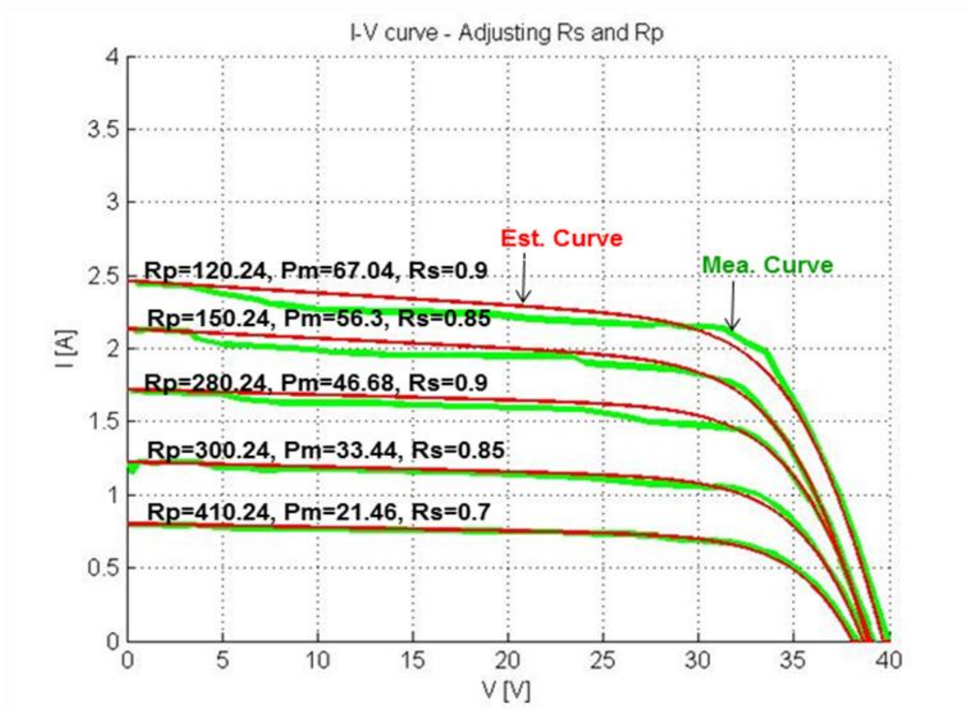


Figure 30: Rp and Rs on IV curves for 27.73g dusty PV panel

Table 7 Summary of IV curves for 27.73g dusty PV panel

No.	Time	Temp (Cell) (°C)	Irrad (W/m²)	Eff. Irrad (W/m²)	Voc (V)	Isc (A)	Pm (W)	Dust Index	Iterative method	
									Rs (Ω)	Rp (Ω)
1	1:22 PM	32.6	691	492	40	2.462	67.04	0.712	0.9	120.24
2	1:53 PM	36.1	600	425	39.15	2.135	56.13	0.7083	0.85	150.24
3	2:20 PM	33.9	495	345	39.2	1.719	46.68	0.697	0.9	280.24
4	2:54 PM	33.1	360	245	38.9	1.224	33.44	0.6806	0.85	300.24
5	3:23 PM	30.7	236	160	38.35	0.802	21.46	0.678	0.7	410.24

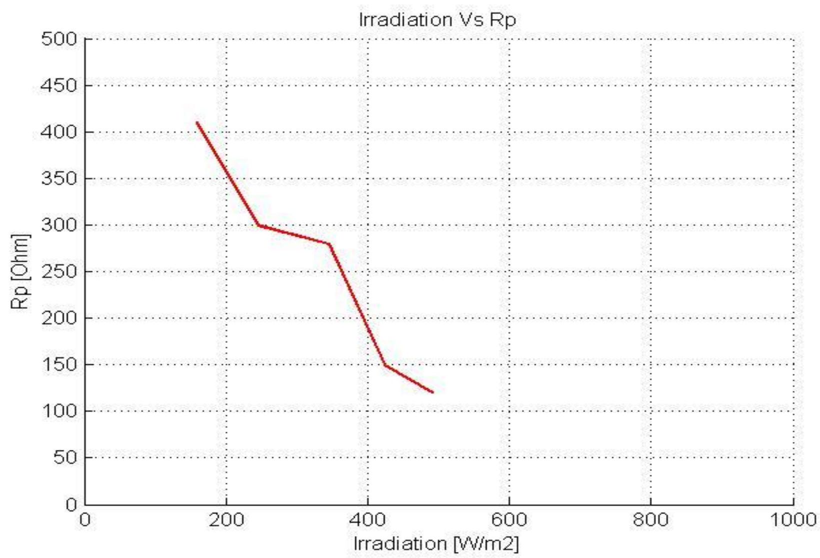


Figure 31: Effect of Irradiation in Rp for 27.73g dusty PV panel

Below Figure 32 shows the comparison of I-V curves and P-V curves for different cases at 900W/m^2. Blue curves of I-V and P-V describes for clean PV panel. Similarly, red, pink, light blue, dotted line blue and green color curves shows the performance of PV on different level of dust. The increasing level of dust causes low powers.

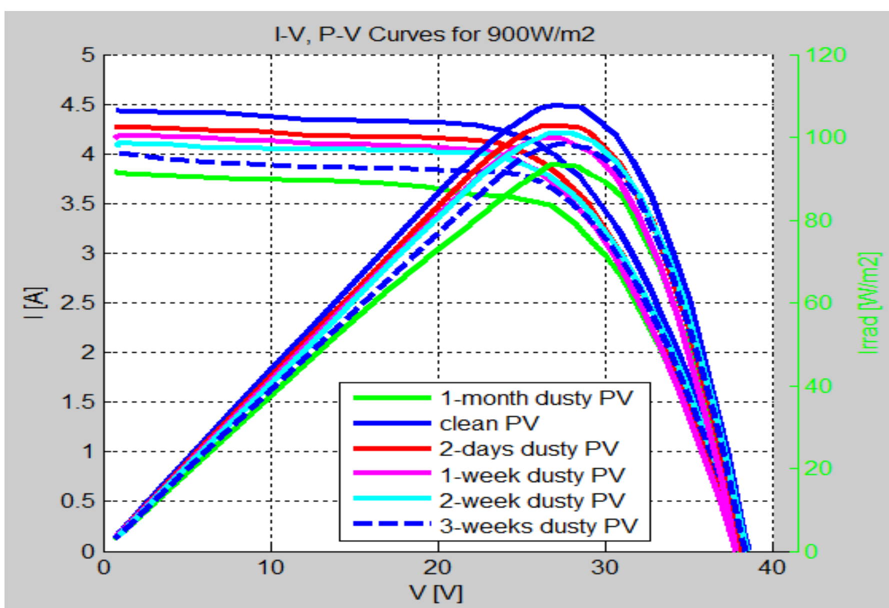


Figure 32: IV and PV curves for different cases at 900W/m^2

Figure 33 has shown the impact of irradiation on the value of Rp for both cases clean and dusty. By the time, when the irradiation reaches to around 700 W/m^2 level, the value of Rp drops to stabilize at a value of 300 Ω as long as the irradiation level is higher than 700 W/m^2 level. In the afternoon, as soon as the irradiation goes back to level of 700 W/m^2 downward, the value of Rp picks up again higher than its value at the valley of the curves. For the dusty case, similar behavior is experimented. When the irradiation level picks up in the morning, the value of Rp drifts down and stabilizes at a range of 120-150 Ω till the afternoon time when the irradiation goes down to 500W/m^2, then the value of Rp picks up again. Similarly, the clean (upper pink curve) shows higher Rs values as compared to Rs values for a month dusty (lower cyan curve) PV panels as shown in Figure 34. These describe the stable values of Rp and Rs at high irradiation and increases as irradiation decreases. Figure 35 demonstrate the effect of temperature on the value of Rp. The dusty and clean behaviours of Rp in Figure 33 are now displayed in Figure 35 as function of irradiation. For each clean and dusty case, the two half days are supposed to be superimposed but due to temperature effect, such as the values of Rp at (46.33 °C & 46.3 °C) is higher than the corresponding value at (30.8 °C & 32.5 °C) respectively. Similar behavior is observed for the dusty case for value of Rp at (35.5 °C & 36.1 °C) with respect to the value of Rp at (25.4 °C & 25.4 °C). At high irradiation the temperature effect is not much affected but Rp increases as temperature goes high at low irradiation. This summarizes in Table 8 &

Table 9 for clean PV panel (20April14) and month dusty panel (07Nov13).

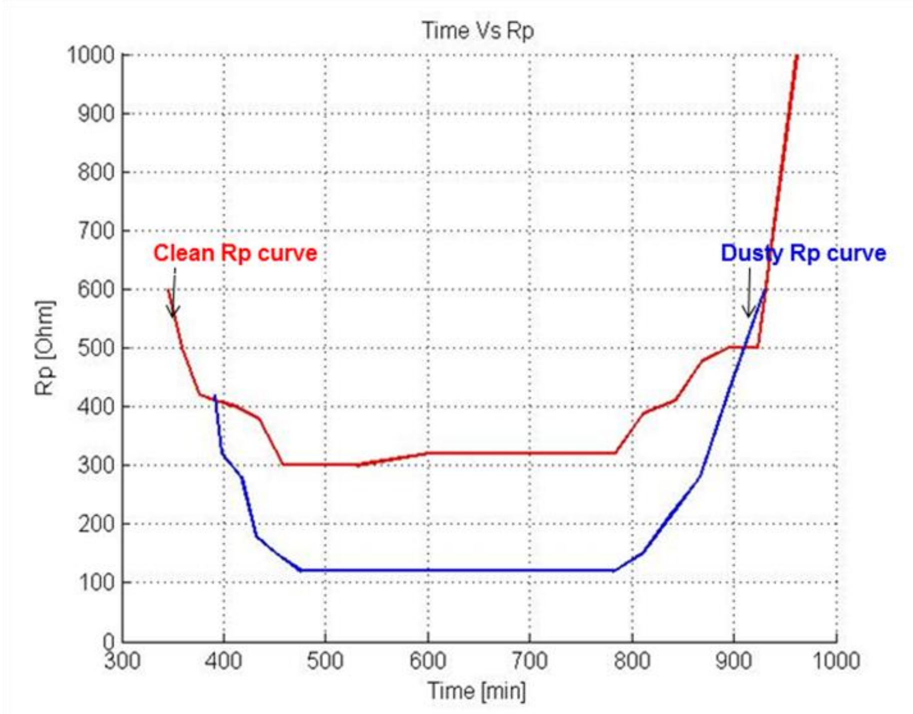


Figure 33: Comparison of Rp for clean and 1month dusty PV panel

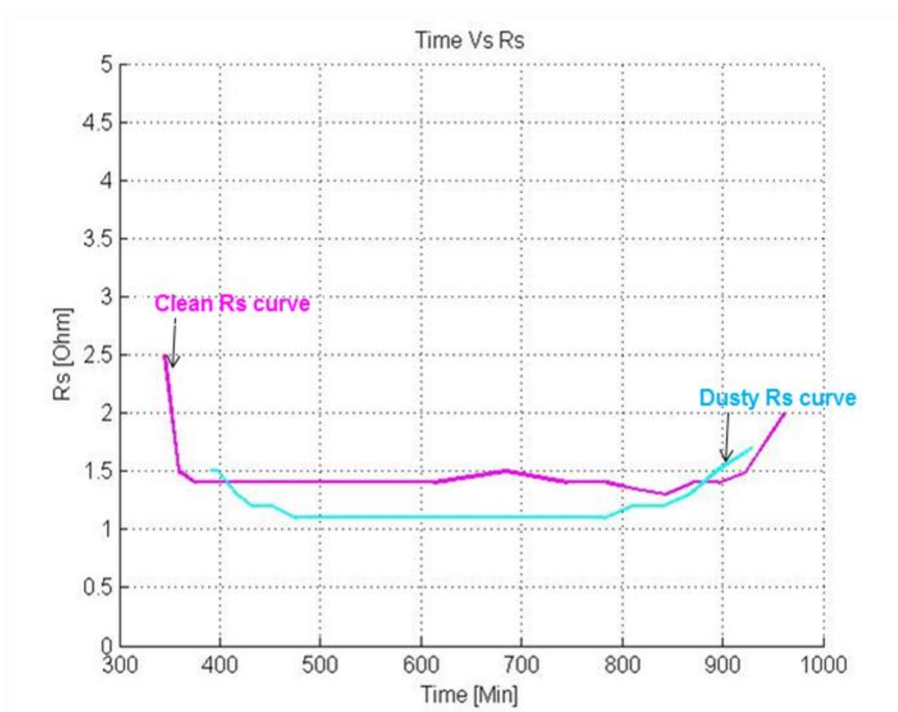


Figure 34: Comparisonof Rs for clean and 1 month dusty PV panel

Table 8 Summary of Rp & Rs for clean PV panel

No.	Time	Temp (Cell) (°C)	Irrad (W/m²)	Voc (V)	Isc (A)	Pm (W)	Iterative method	
							Rs (Ω)	Rp (Ω)
1	5:45 AM	27.6	128.4	38.55	0.719	19.13	2.5	600
2	5:58 AM	28.8	204.1	39.5	1.151	31.86	1.5	500
3	6:16 AM	30.8	322	40.1	1.683	47.56	1.4	420
4	6:30 AM	32.5	401.5	40.25	2.09	58.69	1.4	410
5	6:52 AM	35.2	506.2	40.15	2.6	71.39	1.4	400
6	7:14 AM	37.6	602.2	40	3.053	82.1	1.4	380
7	7:39 AM	39.6	710	39.65	3.53	91.97	1.4	300
8	8:07 AM	42.7	802	39.25	3.962	100.34	1.4	300
9	8:50 AM	45.6	895	38.7	4.441	107.94	1.4	300
10	10:01 AM	54.4	967.2	37.3	4.818	110.17	1.4	320
11	10:12 AM	50	986.2	37.8	4.91	112.75	1.4	320
12	11:35 AM	52	912.4	37.45	4.653	105.06	1.5	320
13	12:26 PM	53	803	36.75	4.181	96.3	1.4	320
14	1:04 PM	50.6	698	37.4	3.639	87.19	1.4	320
15	1:32 PM	48.3	602	37.65	3.175	78.32	1.35	390
16	2:03 PM	47.3	504	37.85	2.679	68.34	1.3	410
17	2:30 PM	46.3	407	37.85	2.188	56.77	1.4	480
18	2:55 PM	46.33	310	37.5	1.667	43.64	1.4	500
19	3:23 PM	45.6	190	36.9	1.012	24.67	1.5	500
20	4:02 PM	42.6	105	35.8	0.52	12.78	2	1000

Table 9 Summary of Rp & Rs for 1-month dusty PV panel

No.	Time	Temp (Amb) (°C)	Temp (Cell) (°C)	Irrad (W/m²)	Eff. Irrad (W/m²)	Voc (V)	Isc (A)	Pm (W)	Dust Index	Iterative method	
										Rs (Ω)	Rp (Ω)
1	6:31 AM	25	25.5	235	200	39.65	1.01	29.67	0.851	1.5	420.2
2	6:38 AM	24.8	25.4	295	250	40.05	1.26	35.87	0.847	1.5	320.2
3	6:57 AM	25.2	26.7	420	355	40.5	1.78	51.17	0.845	1.3	280.2
4	7:11 AM	25.6	28.2	505	430	40.6	2.15	61.43	0.851	1.2	180.2
5	7:31 AM	26	29.2	600	510	40.6	2.55	71.97	0.85	1.2	150.2
6	7:56 AM	26.3	31.5	700	595	40.35	2.97	82.04	0.85	1.1	120.2
7	8:28 AM	27.7	34	805	685	40.1	3.43	92.4	0.851	1.1	120.2
8	9:12 AM	29	38.6	900	770	39.4	3.86	99.9	0.856	1.1	120.2
9	10:42 AM	33.7	49.3	900	780	38.25	3.91	95.81	0.867	1.1	120.2
10	11:44 AM	33.5	45.3	810	700	38.4	3.53	89.06	0.864	1.1	120.2
11	12:30 PM	33.8	44.2	700	610	38.55	3.07	79.13	0.871	1.1	120.2
12	1:02 PM	33.6	41.3	610	530	38.9	2.67	70.77	0.869	1.1	120.2
13	1:31 PM	32.6	37.9	510	435	39	2.2	59.41	0.853	1.2	150.2
14	2:01 PM	32.4	36.1	405	345	38.9	1.73	46.99	0.852	1.2	220.2
15	2:27 PM	32.4	35.5	305	260	38.5	1.3	35.06	0.852	1.3	280.2
16	2:54 PM	32.7	34.2	200	170	37.85	0.85	22.77	0.85	1.5	420.2
17	3:30 PM	31	31.12	75	63	35.55	0.3	7.02	0.84	1.7	600

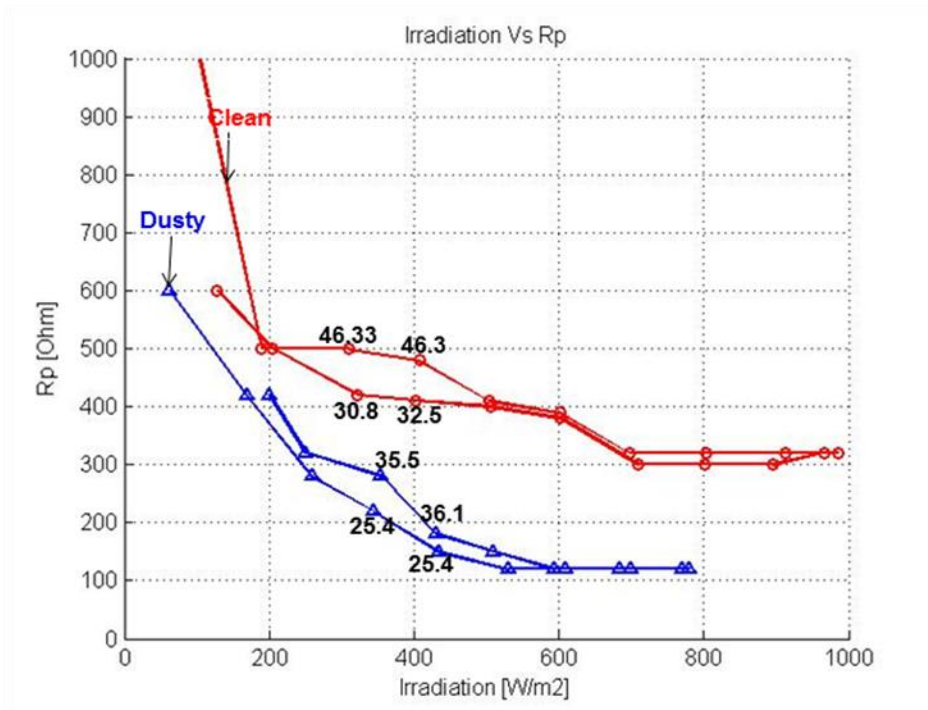


Figure 35: Effect of Temperature in Rp for clean and 1 month dusty PV panel

6.2 PV parameter estimation:

6.2.1 Open circuit behaviour for clean PV panel:

It is required to model the PV panel open circuit voltage (Voc) and short circuit current (Isc) based on experimental data. The objective is to reach a valid model for open circuit voltage based on experimental data that varies with panel temperature and solar irradiation. The suggested model for Voc is shown in equation (16)

$$V_{oc2} = V_{oc1} + K_{Tv}(T_2 - T_1) + K_{Gv}(G_2 - G_1) \tag{16}$$

where K_{TV} and K_{GV} are the parameters considered to be the sensitivity function. Subscripts 'TV' and 'GV' stands for voltage temperature coefficient and voltage irradiation coefficient respectively.

The approach used to estimate K_{TV} and K_{GV} is based on segregating the effect of irradiation and the temperature at one time. To reach the impact of temperature by itself on Voc, we select two points at the same irradiation level but at different temperature for Voc (V_{oc1} and V_{oc2}) at T_1 and T_2. Then, K_{TV} is estimated from relation (16) since the term K_{GV} (G_2-G_1) is cancelled. These operations were repeated for several irradiation values from 967.2 down to 438W/m^2. Similarly, to reach the impact of irradiation by itself on Voc, we select two points at the same temperature but at different irradiation level for Voc (V_{oc1} and V_{oc2}) at G_1 and G_2. Then, K_{GV} is estimated from relation (16) since the term K_{TV} (T_2-T_1) is cancelled. These operations were repeated for several temperature values from 45.7 down to 35.3^{o}C.

The extracted values for K_{TV} and K_{GV} and all related data are shown in

Table 10 and Table 11 (15Mar14).

The temperature impact is more pronounced and influenced on Voc when compared with the impact of irradiation on Voc. K_{TV} was found to be 0.25[V/K] as an average value. K_{GV} average shows a much less impact of the variation of the irradiation on Voc. As a matter of demonstration Figure 36 shows a continuous decay of Voc with panel temperature. The sensitivity of Voc with respect to solar irradiation is immediate but not much pronounced. As an example a sharp dip in irradiation from 900 to 300W/m^2 has caused Voc voltage drop from 38 to 36V.

Table 10 Results for K_T

Irrad (W/m^2)	**$Temp_1$ (^oC)**	**$Temp_2$ (^oC)**	**V_{oc1} (V)**	**V_{oc2} (V)**	**K_T (V/C)**
930.7	35.9	45.2	39.75	38.35	-0.1505
948.9	36.7	45.7	39.65	38.25	-0.1555
967.2	40	43.9	39.1	38.45	-0.1666
912.4	39.6	44.4	39	38.35	-0.1354
784.7	41.3	45.6	39.15	38.1	-0.2442
748.2	39.1	43.6	39.6	38.65	-0.2111
821.2	38.5	43.1	39.05	38.65	-0.0869
821.2	43.1	46.6	38.65	38.2	-0.1286
638.7	30.1	37.2	41.2	39.6	-0.2254
620.4	33.4	40.8	40.35	38.75	-0.2162
620.4	33.4	37.4	40.35	39.45	-0.225
438	35.3	36.5	39.4	39.15	-0.2083

.

Table 11 Results for K_G

Temp (^oC)	Irrad$_1$ (W/m^2)	Irrad$_2$ (W/m^2)	V_{oc1} (V)	V_{oc2} (V)	K_G (V/W/m^2)
45.2	912.4	930.7	38.3	38.35	0.0027
45.7	912.4	948.9	38.15	38.25	0.0027
43.9	912.4	967.2	38.35	38.45	0.0018
44.4	328.5	912.4	36.35	38.35	0.0034
45.6	784.7	912.4	38.1	38.2	0.0008
43.5	894.2	967.2	38.35	38.65	0.0041
43.1	273.7	821.2	36.5	38.65	0.0039
37.2	182.5	638.7	36.7	39.6	0.0064
40.8	620.4	857.7	38.75	38.9	0.0006
37.3	200.7	948.9	37.25	39.5	0.003
35.3	146	438	37	39.45	0.0084

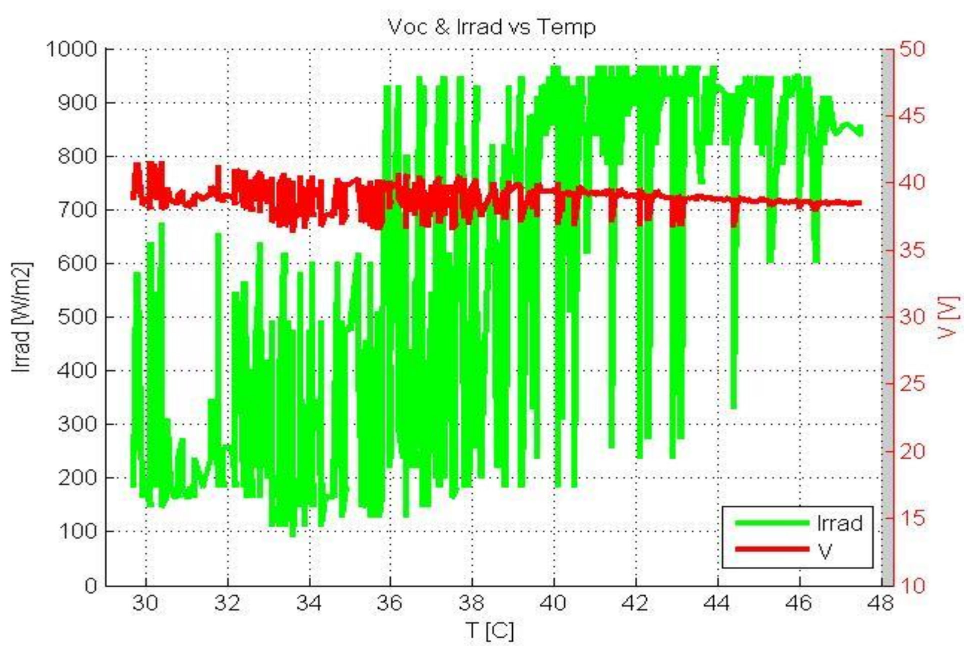


Figure 36: Voc and Irradiation versus Cell Temperature for clean PV panel

6.2.2 Short circuit behaviour for clean panel:

The objective is to reach the impact of irradiation and temperature on the short circuit current. The approach to estimate K_I based on the suggested model shown in equation (17).

$$I_{sc} = (I_{scn} + K_I (T - T_n)) * \frac{G}{G_n} \tag{17}$$

The approach was by considering a short circuit for the whole day and for the clean PV panel. The irradiation, panel temperature and panel short circuit current measurement were taken. The measurement time interval was five minutes and the total measurement time was 15 hours to cover the whole clear with a clean panel day. Figure 37 is displaying the irradiation variation in blue color superimposed on the variation of the short circuit current (red color). The linearity factor found was a constant around value 200 i.e as shown by relation (18).

$$G = C * I_{sc} \tag{18}$$

The short circuit follows immediately the variation of the irradiation. The green color depicts the panel temperature changes with time but no significant impact on the short circuit current. In this analysis we consider the panel temperature as the aggregate resulting effect of wind speed, humidity, ambient temperature etc.

The obtained value of K_I varies from 0.02 – 0.2[A/K]. An average value of K_I was estimated at 0.07[A/K] for most of the time during at practical irradiation level about 400 – 1100W/m^2. It is noted that a sudden increase in K_I values synchronized with the sudden decrease in irradiation. K_I is mainly effected by the irradiation its temperature dependence is minor.

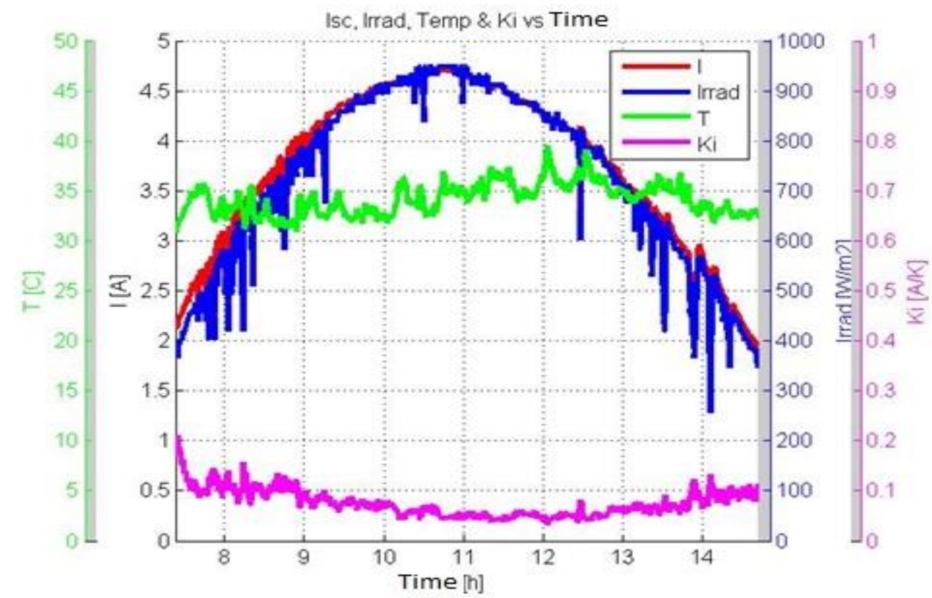


Figure 37: Isc, Irrad., Temp. & Ki Versus Time for clean PV panel

6.2.3 Open circuit behaviour for dusty panel:

Similarly to the clean panel, to reach the impact of temperature by itself on Voc for dusty PV panel, we select two points at the same irradiation level but at different temperature for Voc (V_{oc1} and V_{oc2}) at T_1 and T_2. Then, K_{TV} is estimated from relation (16) since the term K_{GV} (G_2-G_1) is cancelled. These operations were repeated for several irradiation values from 1003.6 down to 346.7W/m^2. Similarly, to reach the impact of irradiation by itself on Voc for dusty PV panel, we select two points at the same temperature but at different irradiation level for Voc (V_{oc1} and V_{oc2}) at G_1 and G_2. Then, K_{GV} is estimated from relation (16) since the term K_{TV} (T_2-T_1) is cancelled. These operations were repeated for several temperature values from 42.2 down to 30.6°C. The extracted values for K_{TV} and K_{GV} and all related data are shown in Table 12 & Table 13 (16Mar14).

The temperature impact is more pronounced and influenced on Voc when compared with the impact of irradiation on Voc. K_{TV} was found to be 0.139 [V/K] as an average value for the dusty case. K_{GV} average shows a much less impact of the variation of the irradiation on Voc.

Table 12 Results for K_T for dusty panel

Irrad (W/m^2)	**Temp1 (°C)**	**Temp2 (°C)**	**Voc1 (V)**	**Voc2 (V)**	**K_T (V/C)**
1003.6	35.3	40.6	39.2	38.65	-0.1038
985.4	34.2	42	39.35	38.5	-0.109
967.2	35.1	44.1	39.3	38.25	-0.1166
930.7	35.5	38	39.3	38.95	-0.14
894.2	34	41.9	39.5	38.5	-0.1266
802.9	30.5	41.9	40.05	38.4	-0.1447
766.4	27.7	40	40.4	38.55	-0.1504
656.9	26	42.2	40.55	38.3	-0.1389
547.4	22.8	35.8	40.75	38.85	-0.1461
456.2	20.8	37.5	40.8	38.45	-0.1407
419	20.7	36.3	40.65	38.45	-0.141
346.7	19.4	35.1	41.5	38.2	-0.2102

Table 13 Results for K_G for dusty panel

Temp (^oC)	**Irrad1 (W/m^2)**	**Irrad2 (W/m^2)**	**Voc1 (V)**	**Voc2 (V)**	**K_G ($V/W/m^2$)**
40.6	967.2	1003.6	38.55	38.65	0.0027
42	656.9	985.4	38.3	38.5	0.0006
42.2	656.9	821.2	38.3	38.5	0.0012
41.9	802.9	894.2	38.4	38.5	0.0011
41.3	948.9	985.4	38.45	38.55	0.0027
40	766.4	930.7	38.55	38.8	0.0015
39.9	675.2	1003.6	38.6	38.7	0.0003
35.8	547.4	985.4	38.85	39.35	0.0007
37.5	456.2	985.4	38.45	39	0.001
35.1	346.7	985.4	38.2	39.3	0.0017
33.6	620.4	875.9	39.15	39.55	0.00156
30.5	146	802.9	36.95	40.05	0.0047

6.2.4 Short circuit behaviour for dusty panel:

Similarly to the clean panel, the short circuit (red color) for dusty panel follows the irradiation changes as shown in Figure 38. Differently from the short circuit of clean panel, the dusty panel current is no longer proportional to the irradiation by the factor of 200 as discussed earlier. The dependency ratio is now a function of the dust level. Further dust is accumulated so less short circuit current is flowing. We can later extract the relation between clean and dusty panel short circuit currents.

Figure 38 confirm again the non-sensitivity of the short circuit to the panel temperature. Based on the collected data, the estimated value for the constant K_I varies from 0.01 to 0.1[A/K]. K_I has taken an average of 0.03[A/K] along the significant irradiation (from 500 to 110 W/m^2) that reflects the low impact of temperature on the short circuit current.

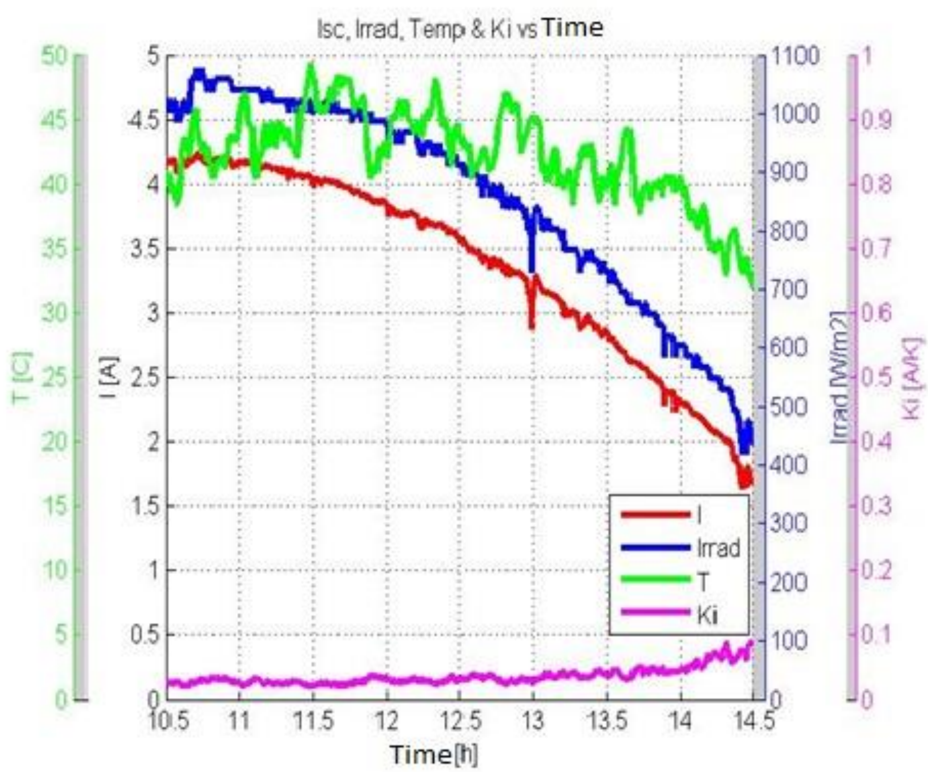


Figure 38: Short circuit current behavior for dusty PV panel

6.3 Improved PV parameter estimation:

6.3.1 Exponential relation for estimated Voc & Isc:

This is an attempt to improve the accuracy of the Voc and Isc based on relation (16) and (17) that used linear approach analysis. This present modified model is described by relations (19), (20) and (21). New function computes the normal cumulative distribution function (cdf) at each time values using the corresponding mean, mu (μ) and standard deviation, sigma (σ) that describes the shape of the Voc curve. The new function is represented as

$$F(x \mid \mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} e^{\frac{-(t-\mu)^2}{2\sigma^2}} dt \tag{19}$$

The new parameters (K_G and K_T) were estimated using the equations

$$V_{oc} = V_{ocn}(normcdf)\left(\frac{T_n}{T}\right)^{K_{TV}}\left(\frac{G}{G_n}\right)^{K_{GV}} \tag{20}$$

$$I_{sc} = I_{scn}(normcdf)\left(\frac{T_n}{T}\right)^{K_{TI}}\left(\frac{G}{G_n}\right)^{K_{GI}} \tag{21}$$

Figure 39 is the follow up of the Voc with irradiation in the whole period of the day. Both rise up and fall down of the Voc at left and right side of the curve are controlled by sigma (σ). The width of the curve on its plateau is controlled by mu (μ). In our case sigma is 40 and mu is 20.

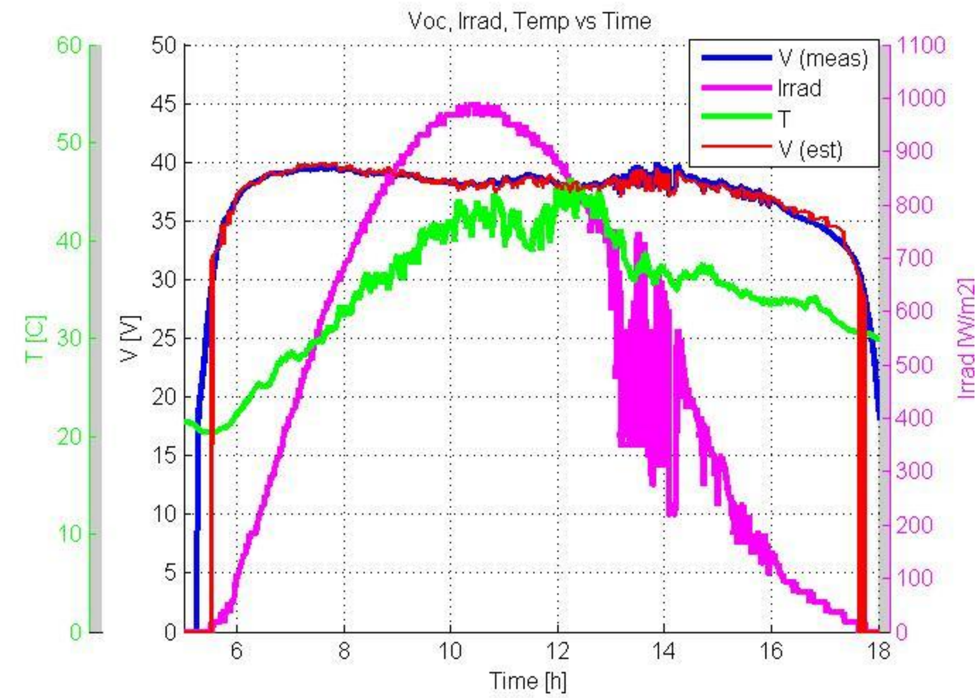


Figure 39: Rise and Fall of Measured and Estimated Voc

The behavior of the open circuit voltage (Voc) with panel temperature and irradiation is described by relation (20). The constant K_{TV} and K_{GV} are found by manual iteration. The same approach was used for the dusty PV panel.

6.3.2 Validation and sensitivity analysis:

The effect of the modifications on the equation accuracy for the clean PV model is considered here. Figure 40 is displaying experimental open circuit voltage (blue curve), irradiation (pink curve), panel temperature (green curve) and modelled (estimated) voltage (red curve) for clean PV panel.

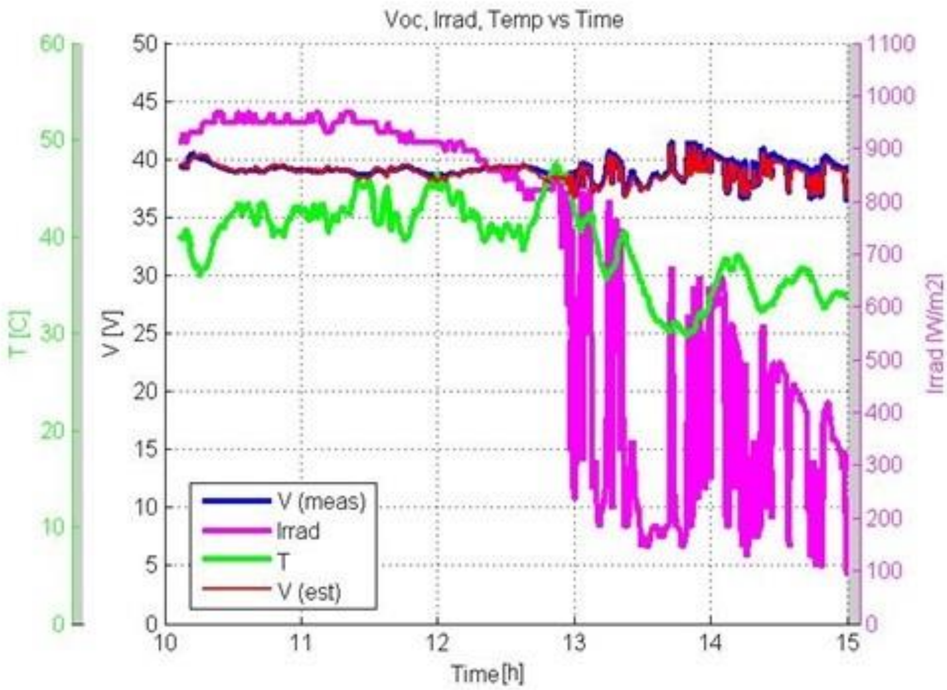


Figure 40: Measured and Estimated Voc for clean PV panel

The red curve is based on equation (20) that following with very good precision the measurement blue curve. Consequently, the irradiation and temperature of the panel are reflected on the estimated Voc.

Figure 41 is displaying measured short circuit current (blue curve), irradiation (pink curve), cell temperature (green curve) and modeled estimated current (red curve) for clean PV panel. The parameters have its own scaled in same graph. The red curve is based on equation (21) and it is following with very good precision the measurement curve (blue color). It is noted that when the short circuit current is multiplied with the scaled factor of 200 then the short circuit current curve is completely super-imposed with the irradiation curve.

These equations provided consistent and significant improvement for clean PV panel. The values of the two new parameters (Kv and Ki) required for the clean PV panels considered in the present study are listed below.

$K_{TV} = 1.65$ & $K_{GV} = 0.05$, $K_{TI} = 0.02$ & $K_{GI} = 0.9$

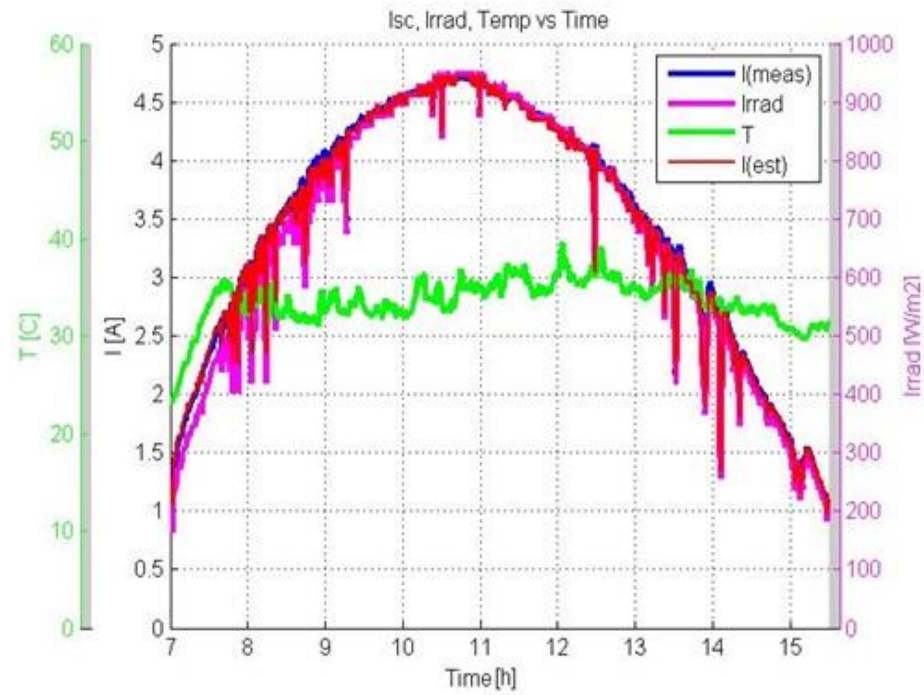


Figure 41: Measured and Estimated Isc for clean PV panel

Similarly, the effect of the modifications on the equation accuracy for the dusty PV panel are considered here and shown in the below figures. Effective irradiation is found for a particular amount of dust from the below equation. The average value of G and I ratio is found as 200 for the clean PV panel. In this case 34.47g weighted dust is distributed over the PV panel.

$$G_{effect} = \frac{G}{I} * I_{effect} \tag{22}$$

Figure 42 is displaying measured experimental open circuit voltage (blue curve), irradiation (pink curve), panel temperature (green curve) and modelled (estimated) voltage (red curve) for a dusty PV panel. Figure 43 is displaying experimental short circuit current (blue curve), irradiation (pink curve), cell temperature (green curve) and modeled current (red curve) for dusty PV panel.

The red curves in Figure 42 and in Figure 43 are based on equation (20) and equation (21) respectively and they are following with very good precision the corresponding measurement blue curves. The values of the two new parameters (Kv and Ki) required for the dusty PV panels considered in the present study are listed below.

$K_{TV} = 2.05$ & $K_{GV} = 0.06$, $K_{TI} = 0.02$ & $K_{GI} = 0.95$,

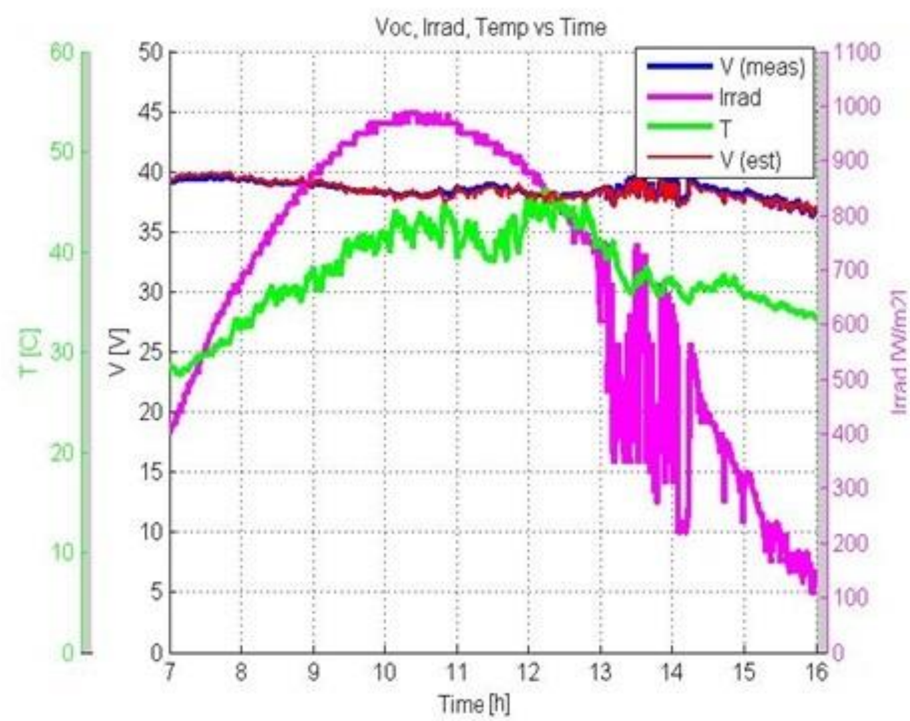


Figure 42: Measured and Estimated Voc for dusty PV panel

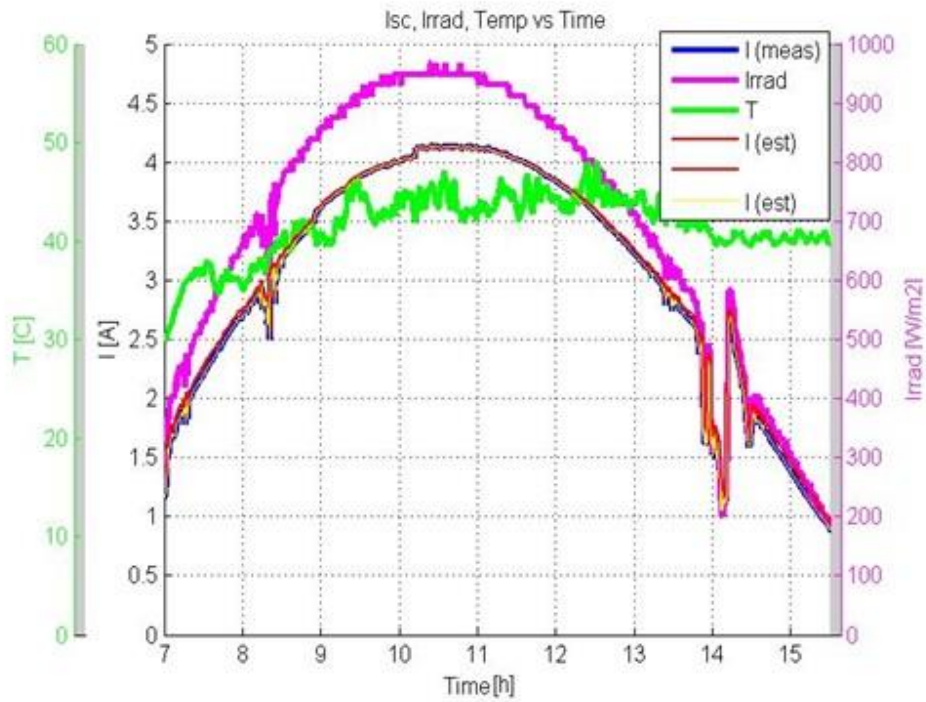


Figure 43: Measured and Estimated Isc for dusty PV panel

6.4 Estimation of maximum power:

For plotting IV curves having only temperature and irradiation, the third and most important parameter maximum power (Im, Vm) is required along with open circuit voltage and short circuit current. A good estimation of maximum power point voltage and current is needed for better results.

The ratios for short circuit currents and maximum power point currents of clean PV panel are found to be in the range 0.86 to 0.93. The average factor for estimation of Im is as follows.

$$I_m = 0.89 * I_{sc} \tag{23}$$

The voltage is mainly affected by the cell temperature. The estimated relation for maximum power point voltage with temperature is found through basic quadratic curve fitting method as indicated by equation and shown in Figure 44.

$$V_m = (-0.0064265*(T)^\wedge 2)+(0.29153*T)+28.205) \tag{24}$$

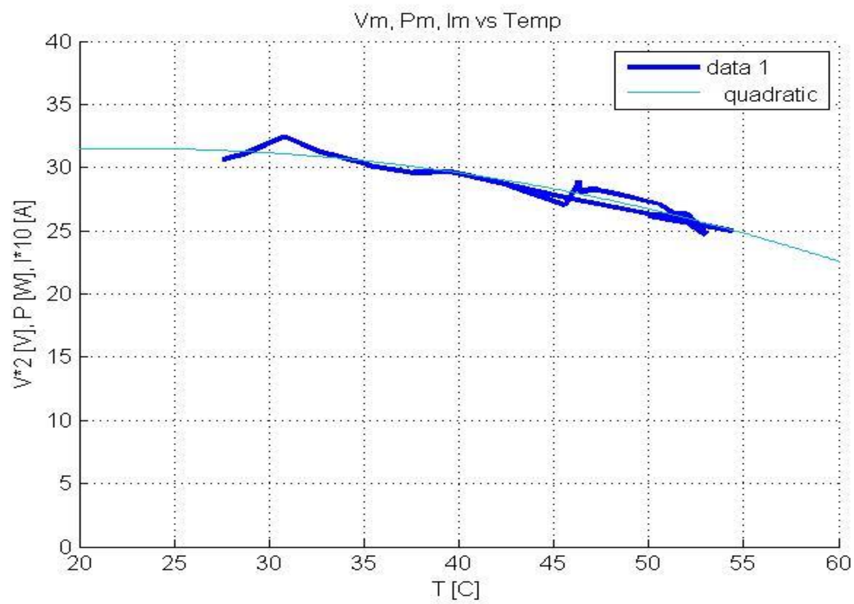


Figure 44: Curve fitting method for Vm of clean PV panel

CHAPTER 7

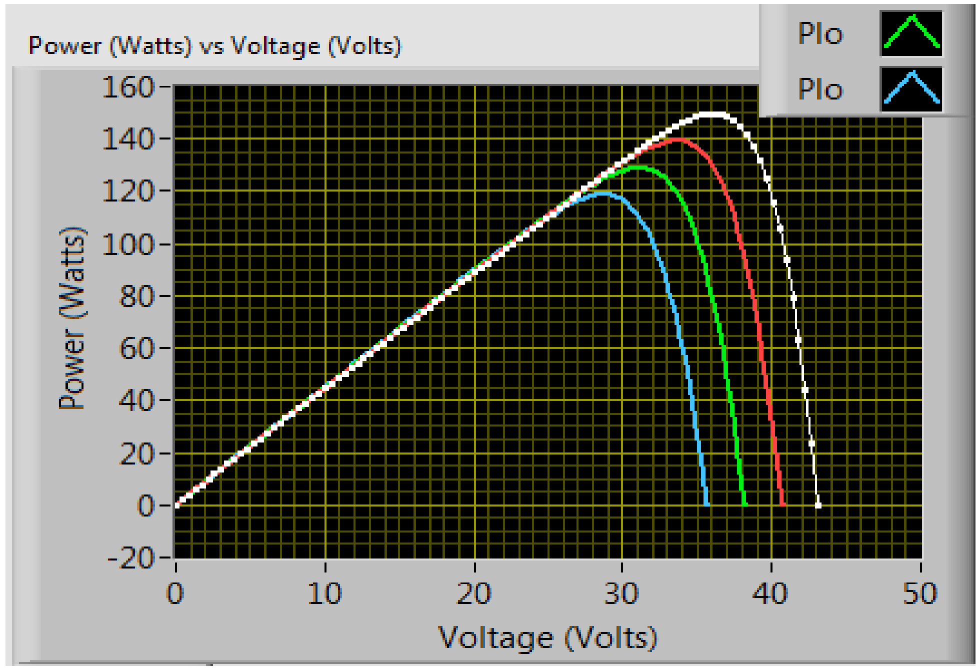
RESULTS AND DISCUSSIONS

7.1 Modeling of PV panel

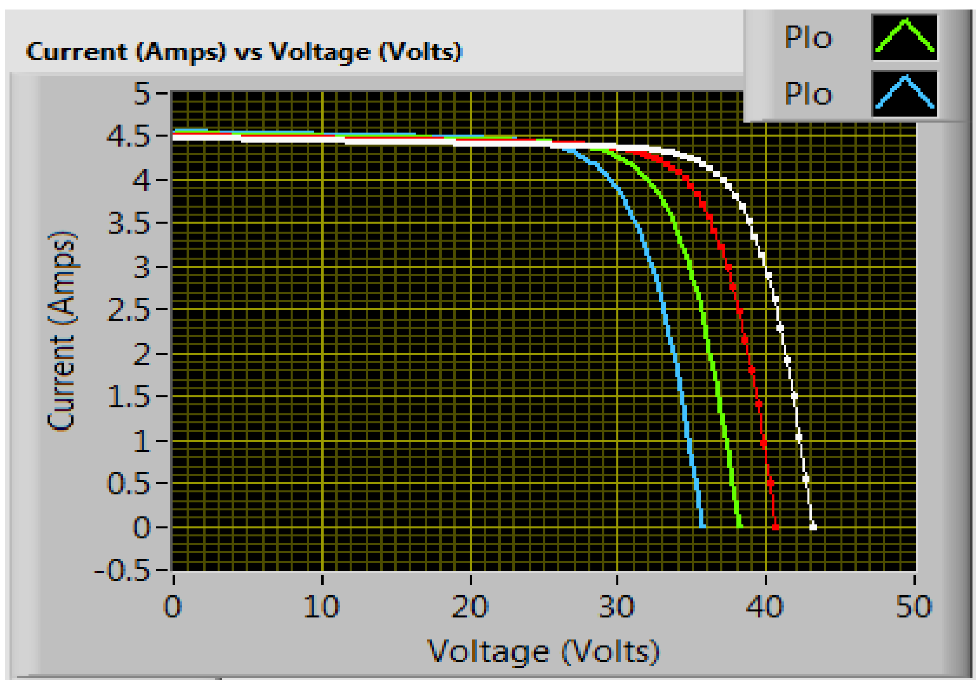
I-V & P-V curves of model are being verified having cell temperature dependence by plotting four curves of different temperatures PV characteristics. It can be seen that maximum power, open circuit (Voc) voltage & short circuit (Isc) current are in acceptable agreement with the values of datasheet.

The relevant module is designed to obtain I-V and its corresponding P-V curve. The evaluation of maximum power point is very important and to be determined by I-V and P-V curves. Figure 45(b) shows four I-V curves (white, red, green and blue at cell temperatures of 25^{o}C, 35^{o}C, 45^{o}C and 55^{o}C respectively) are super imposed in one graph for analysis and performance evaluation and their corresponding P-V curves (white, red, green and blue) are super imposed in one graph for analysis and determination of maximum power points. The results are summarized in

Table 14



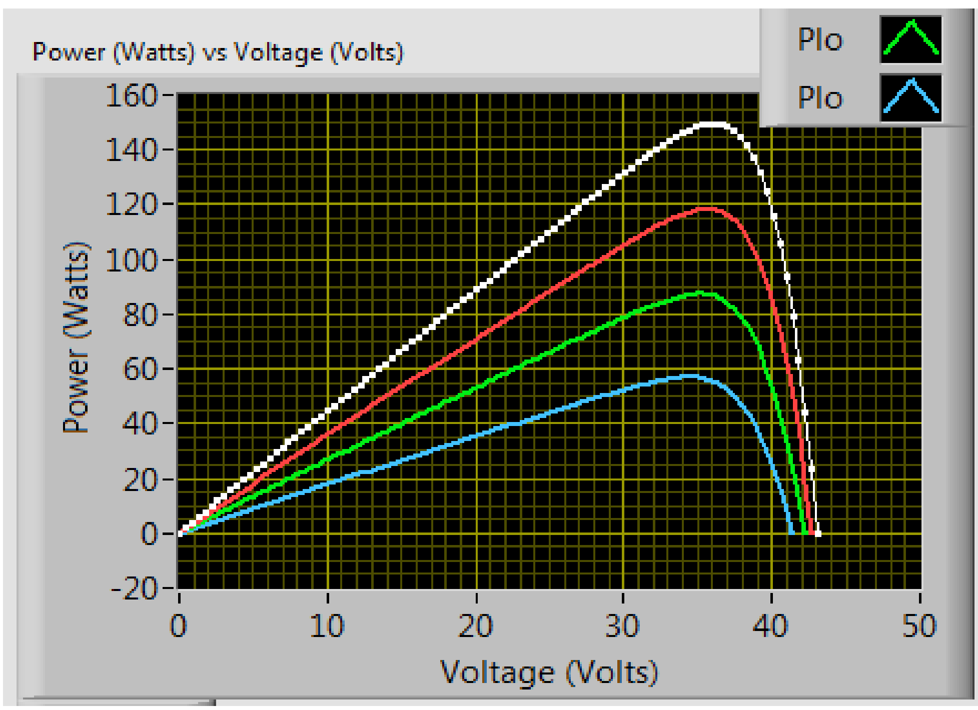
(a) P-V curves



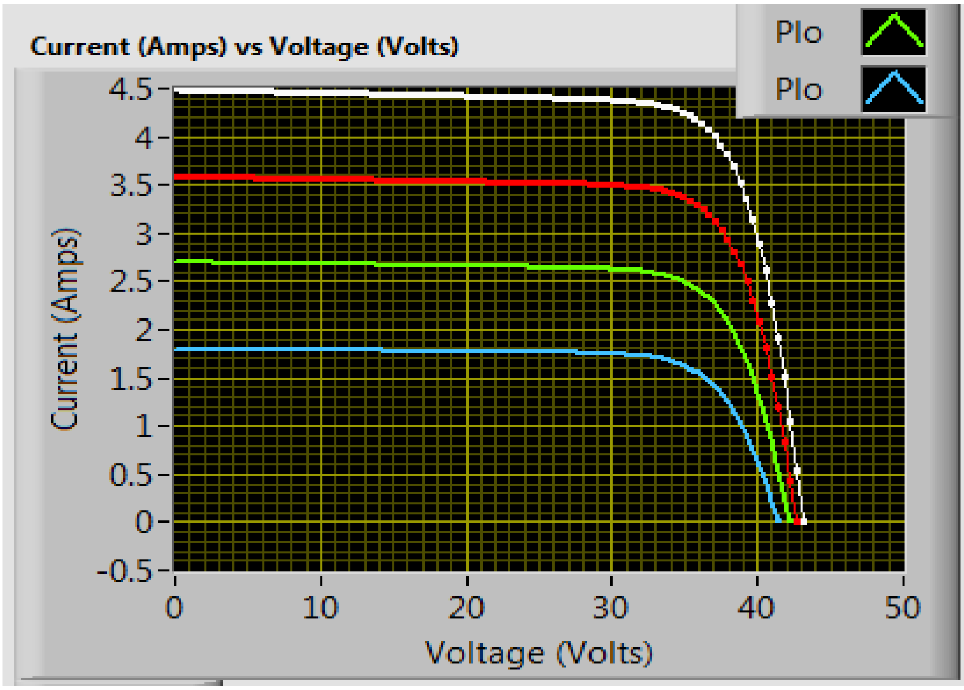
(b) I-V curves

Figure 45: PV characteristics at different temperatures (a) P-V curves (b) I-V curves

Figure 46 is displaying both I-V & P-V curves for solar panel at four different level of irradiation. The white, red, green and blue I-V curves with their corresponding white, red, green and blue consecutively P-V curves are attributed to the irradiation level of $1000W/m^2$, $800W/m^2$, $600W/m^2$ and $400W/m^2$ respectively. Though this figure reveals similar behavior as in above Figure 46 but demonstrate clearly the impact of irradiation level on the performance on the PV panels. According to theory, the Isc (short circuit currents) have a linear dependence with radiation intensity, unlike Voc (open circuit voltages), that increases logarithmically with the irradiation. The results are summarized in Table 14.



(a) P-V curves



(b) I-V curves

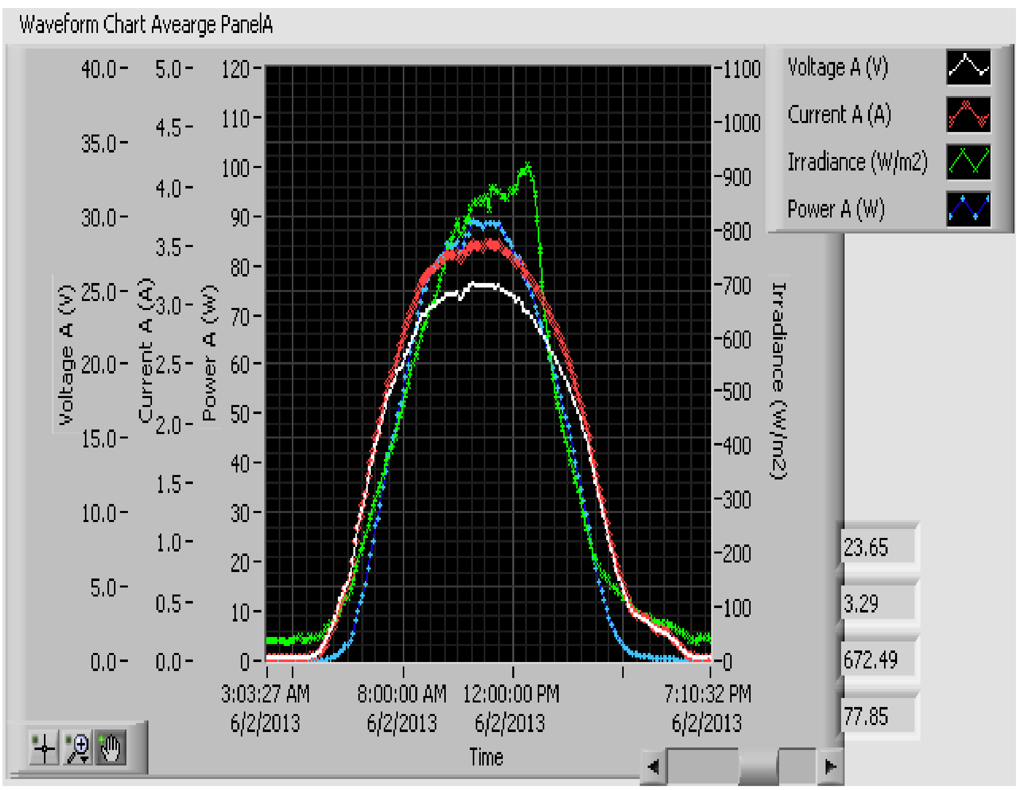
Figure 46: PV characteristics at different irradiation (a) P-V curves (b) I-V curves

Table 14: Model parameters values

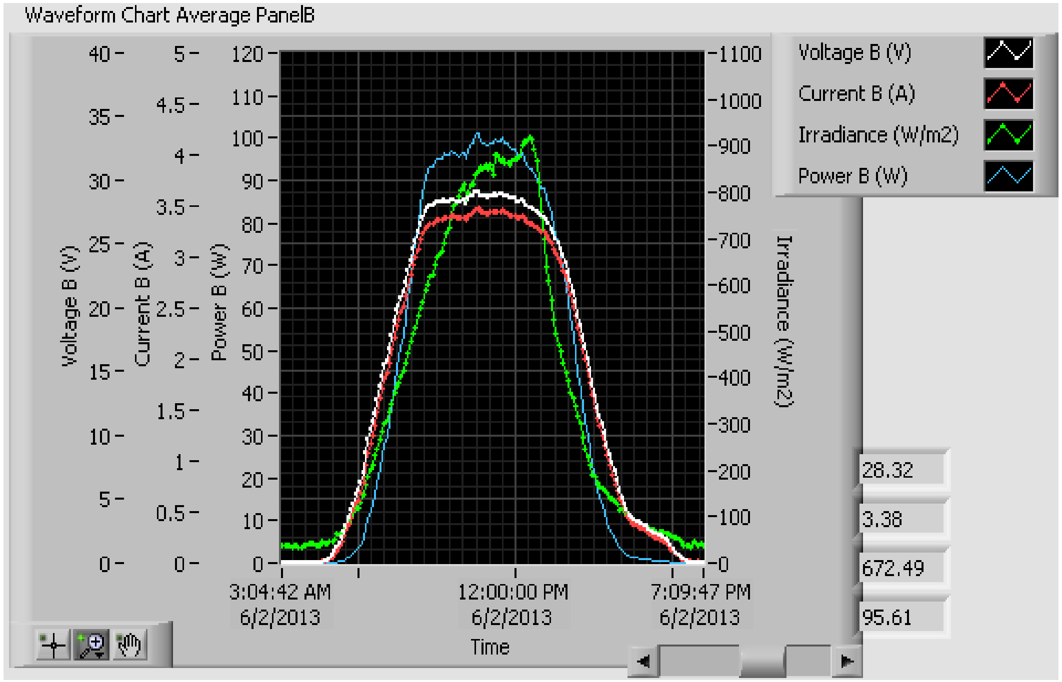
Parameters of model at nominal condition			
Vocn	43.2	Ns	72
Iscn	4.49	a	1.3
Imp	4.16	Io	7.09E-08
Vmp	36	Ipv	4.49084
Ki	0.00212	Rs	0.1004
Kv	-0.0991	Rp	535.115

7.2 LabVIEW based results

Panel A is dusty and panel B is clean, but both panels A & B are exposed to the same environmental conditions such as humidity, wind speed, irradiation and load resistance. Figure 47(b) clearly shows higher level of power output and larger flat curve (plateau). The plateau starts at 9am until 12:20 PM for a level of 95.2W to 95.6W while corresponding curve zone of the dusty panel A starts at 9:30am until 12am for a level of 84.2W to 83.9W. The harvest energy from the clean panel is clearly much higher than the energy harvested from the dusty panel. The maximum power difference is 12.25% at low dust exposition level.



(a) Online dusty panel A



(b) Online clean panel B

Figure 47: Displayed graph for: (a) Online dusty panel A (b) Online clean panel B

Figure 48 shows the online monitoring of both panels output power for two consecutive days. The displayed results show the consistency of the clean panel (red colour) behaviour in harvesting more energy than the dusty panel (white colour). The importance of keeping the panel clean to harvest more power is emphasized by this module. Several factors such as the dust level, the ambient and the panel temperatures, the day time irradiation level and the surrounding hot or cold air affect the maximum output power of the panel for the fixed resistive load. The evaluation of maximum power point is very important and to be determined by I-V and P-V curves. The relevant module is designed to obtain I-V and its corresponding P-V curve at any desire time while the online monitoring modules are ON and the online data is being in streaming position and recorded. Figure 49 shows three I-V curves (green colour) for the clean panel and their corresponding P-V curves (yellow colour) and three I-V curves (blue colour) for the dusty panel and their corresponding P-V curves (red colour) are super imposed in one graph for analysis, performance evaluation and determination of maximum power points. The results are summarized in Table 15.

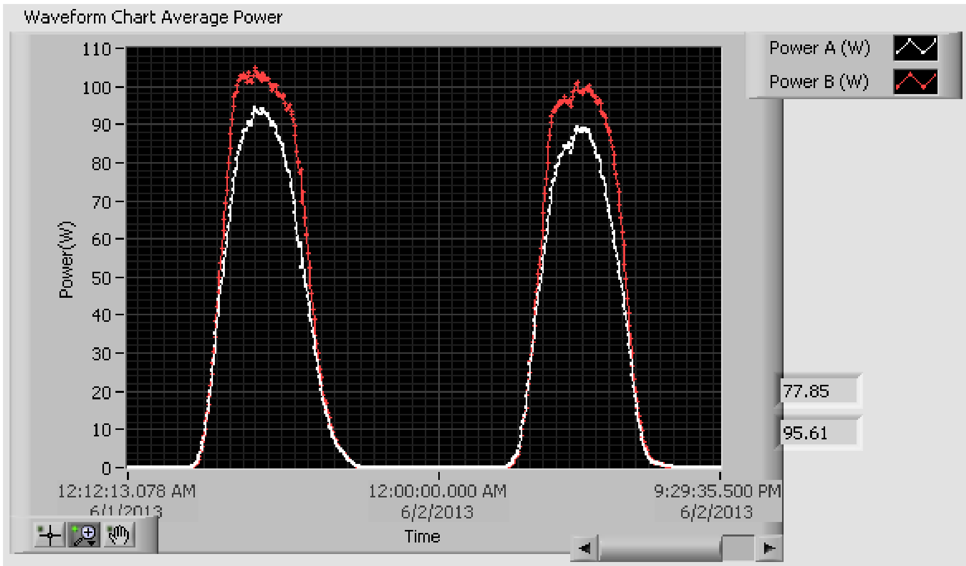


Figure 48: Dusty & clean panel online power for two days

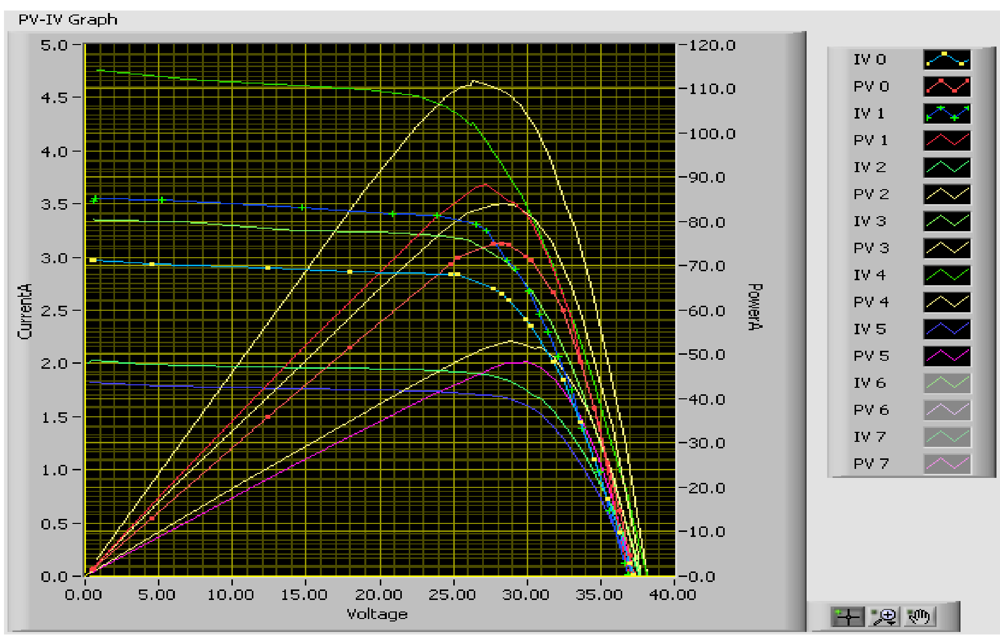


Figure 49: Dusty & clean panel I-V & P-V Curves

Table 15 Results of I-V & P-V curves

Panel	Time	Ambient temp.(°C)	Panel temp.(°C)	Irradiation level(W/m^2)	Max. Power(W)	Voc (V)	Isc (A)
Clean	10:45AM	42.5	49.8	890	111.96	38.14	4.75
Clean	01:15PM	43.3	46.5	560	84.16	37.73	3.35
Clean	2:30 PM	42.5	45.7	270	53.01	37.57	2.01
Dusty	11:20AM	46.6	54.7	940	88.35	36.85	3.56
Dusty	01:30PM	46.4	51.2	490	75.17	37.19	2.98
Dusty	02:30PM	44.3	48.4	270	48.3	37.15	1.83

The relevant module is designed to obtain I-V and its corresponding P-V curve for clean and dusty PV panels. The displayed results show the capability of LabVIEW for super imposing estimated (white colour) and measured (red colour) I-V and P-V curves in one graph for analysis, performance evaluation and determination of maximum power points. The above I-V and P-V curves of clean PV panel displayed in Figure 50 shows the consistency in harvesting more energy at 400W/m^2 and 600W/m^2 irradiation level than the dusty panel shown below in Figure 51.

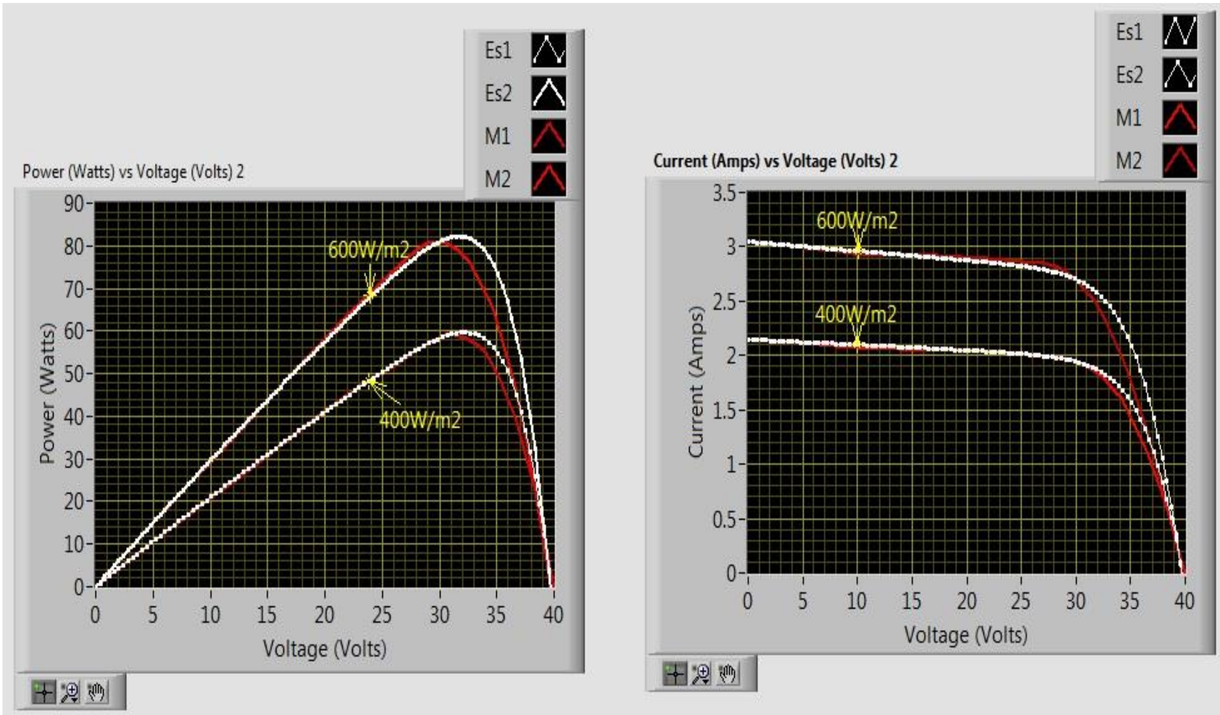


Figure 50: Estimated and measured IV and PV curves of clean PV panel

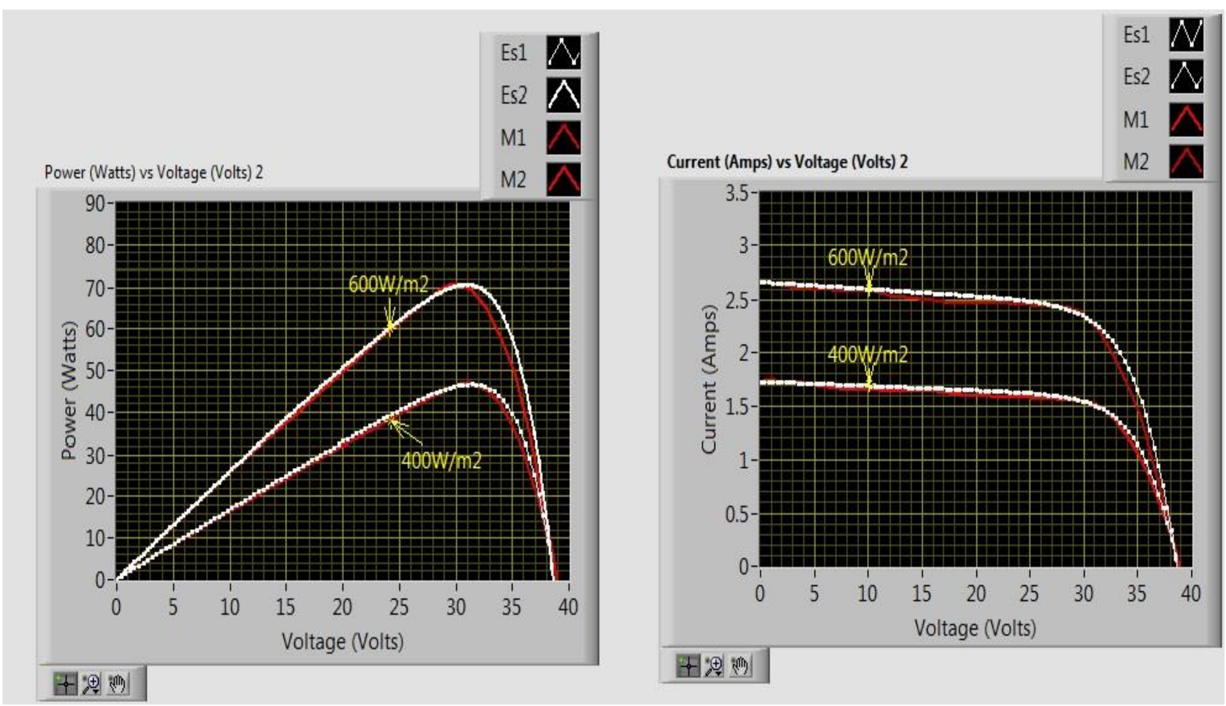


Figure 51: Estimated and measured IV and PV curves of dusty PV panel

7.3 Estimation based results

The result is shown in the Figure 52 by the comparison of measured maximum power and estimated maximum power. The maximum error is found is 4.2 percent with an average error is 0.5583 percent.

$$Err = \left(\frac{Measuredvalue - Estimatedvalue}{Measuredvalue}\right) * 100 \tag{25}$$

The values of Voc, Isc, Im and Vm must be accurate for the best result of I-V curves. The slight difference causes more error in the curvature of I-V curves. Manually, the formation of I-V curves takes around 7-8 minutes. During this time the irradiation may change causes the changes in the values of short circuit current and maximum power points. That could affect the curvature of I-V curves.

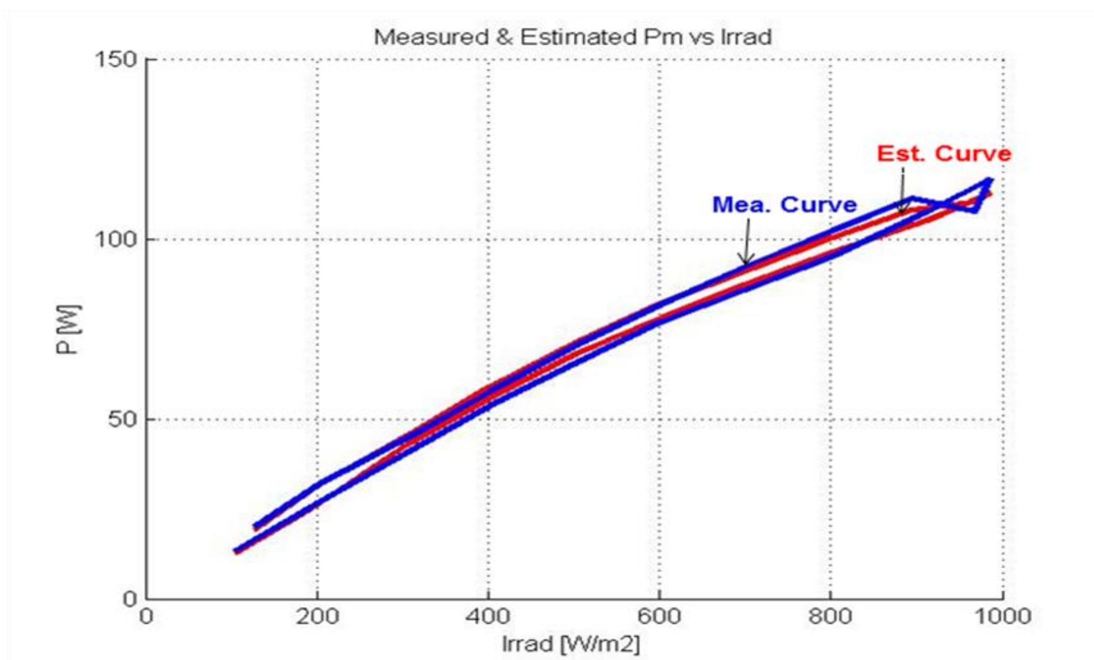


Figure 52: Comparison of measured and estimated Pm of clean PV panel

Now, if we have only temperature and irradiation then we are able to extract the I-V curves for the clean PV panel by estimating the Voc, Isc, Im and Vm values. Similarly, we should have temperature, irradiation and dust index factor for the estimation of these parameters for the dusty PV panel.

Table 16 Comparison of measured values and estimated values for clean PV Panel

Irrad (W/m2)	967.2			802			602		
Temp (C)	54.4			42.7			48.3		
	Measured value	**Estimated value**	**Error (%)**	**Measured value**	**Estimated value**	**Error (%)**	**Measured value**	**Estimated value**	**Error (%)**
Voc (V)	37.3	36.92	1.0188	39.25	38.76	1.2484	37.65	37.01	1.6999
Isc (A)	4.818	4.815	0.0623	3.962	3.97	-0.202	3.175	3.104	2.2362
Imp (A)	4.398	4.285	2.5693	3.514	3.533	-0.541	2.802	2.76	1.4989
Vmp (V)	25.05	25.046	0.016	28.55	28.94	-1.366	27.95	27.29	2.3614
Pmp (W)	110.1699	107.3221	2.5849	100.3247	102.245	-1.914	78.3159	75.3204	3.8249

Table 17 Comparison of measured values and estimated values for dusty PV Panel

Irrad (W/m2)	901			805			600		
Eff. Temp (C)	49.3			45.3			29.2		
Dust index	0.85			0.85			0.85		
	Measured value	Estimated value	Error (%)	Measured value	Estimated value	Error (%)	Measured value	Estimated value	Error (%)
Voc (V)	38.25	37.36	2.3268	38.4	37.89	1.3281	40.6	40.54	0.1478
Isc (A)	3.91	3.919	-0.23	3.53	3.472	1.6431	2.55	2.52	1.1765
Imp (A)	3.459	3.488	-0.838	3.114	3.091	0.7386	2.274	2.243	1.3632
Vmp (V)	27.7	26.96	2.6715	28.6	28.224	1.3147	31.65	31.24	1.2954
Pmp (W)	95.8143	94.03648	1.8555	89.0604	87.24038	2.0436	71.9721	70.07132	2.641

CHAPTER 8

CONCLUSIONS:

This thesis has analyzed mathematical PV panel modeling method and algorithm development in LabVIEW. The purpose is to achieve practical I-V curve of photovoltaic panel without any other parameter estimation except ideality constant a by the method in which experimental remarkable points of PV panel is coincide with mathematical model I-V curves equation. The following datasheet information is required to obtain I-V equation parameters in this method: current & voltage at MPP, output maximum power, short circuit (Isc) current and open circuit (Voc) voltage.

LabVIEW system experimental set-up was built for a standalone PV system to feed a resistive load. The whole integrated system was tested for real time measurements as well as for I-V and P-V characteristics under different environmental conditions.

- LabVIEW shell was tested for clear day time under normal ambient temperature and clean panel conditions. The output power was monitored at real time rate. The stand alone system performance was mainly affected by the irradiation variation during the day. The developed system displayed graphically and recorded relevant voltage, current and power at high frequency measurement and at the designated average time interval.

- The interface capability of displaying several parameters and variables simultaneously in a multi-scale window frame was very useful for analysis purposes. Each panel variable could be monitored separately on real time basis for unlimited number of days. The data is continuously stored and recorded by a file per day.

- The simultaneous performance of PV clean panel and similar dusty panel were investigated using LabVIEW system through the I-V curves along with its corresponding P-V curves for each panel. The appended curve results have demonstrated clearly better performance in favour of the clean panel. LabVIEW graphs have revealed a different slope for the dusty panel I-V curve to declare the change in the electrical parameters such as parallel and series resistance of the dusty panel.

- The automatic appending capability for online environment is a very good feature of the developed LabVIEW system. Power output evaluation as well as the monitoring of panel temperature under different irradiations would be essential for the healthy and efficient system exploitation. System levels evaluation and a comparative feature have been successfully tested and displayed the performance of clean and dusty panels under the impact of different levels of irradiations.

Future Recommendation

There is a need for further PV model development based on experimental data.

The developed PV panel model can be modified by introducing Rp and Rs model for the clean PV panel.

Dusty condition is one of the major issues causes the degradation of efficiencies of PV panel thus, similarly Rp and Rs model for dusty panel can be the subject of further investigation.

Once the PV model is developed including the effect of dust, heat and other environment condition then the PV grid system could be simulated and studied.

Since the heat has large impact on PV performance, then the need for an accurate heat model for PV generator becomes essential. The design of an appropriate cooling system could improve further the PV performance.

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1. "PV-standalone monitoring system performance using LabVIEW", *International Journal of Smart Grid and Clean Energy*, vol. 3, no. 1, January 2014: pp. 44-50.
2. "PV generator performance using Cassy System*", International Conference Renewable Energy Research and Applications*, Oct-2013.
3. "LabVIEW based PV panel characteristics", (ready to be submit)
4. "Parameter estimation of PV panel in extreme environmental conditions", (under preparation).